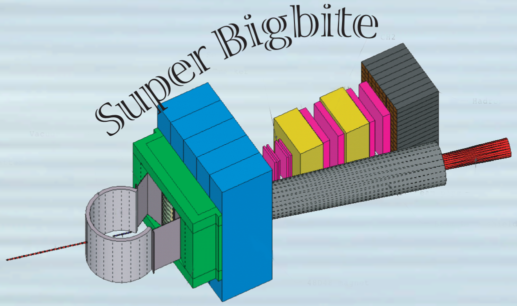
The JLab SBS Program and Nucleon Form Factors at high Q^2

- Some history regarding the role of nucleon form-factor measurements
- How SBS will enable huge advancements in our understanding of high-Q^2 form-factor measurements.
- A quick look at projected results

Gordon D. Cates
September 23, 2019



University of Virginia

Jefferson Lab
EXPLORING THE NATURE OF MATTER

What is SBS?

One answer:

- An acronym for Super Bigbite Spectrometer

A more substantive answer

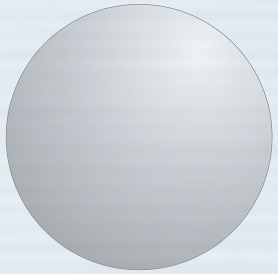
- It is a collection of new equipment that will enable precise measurements of the nucleon form factors to unprecedented values of Q^2

So why measure the nucleon form factors to such high Q^2

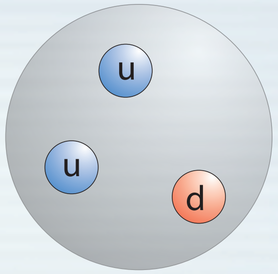
Here it is useful to take a quick look at history….

Studies of elastic FFs have provided a long history of discovery

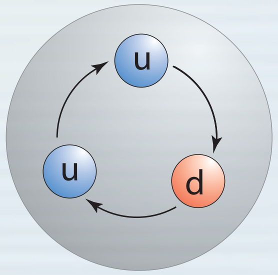
- Hofstadter's studies of the proton form factor (FF)
  - helped establish its size.



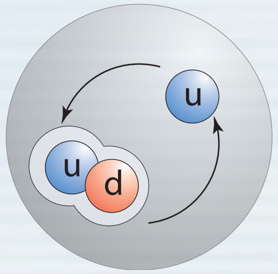
- Studies at SLAC of proton FFs at high Q^2
  - were a key part of the data from SLAC that led to the discovery of quarks



- Discovery at JLab that G_E^p/G_M^p decreases nearly linearly at high Q^2
  - Renewed focus on nucleon structure and the role of quark orbital angular momentum.



- Measurements at JLab of G_E^n/G_M^n high Q^2
  - Provided, for the first time, the ability to separate the behavior of up and down quarks at high Q^2, and important evidence, beyond the missing states in the N* spectrum, for the existence of diquarks.



SLAC proposal from almost 54 years ago

SLAC Proposal No. 4

PROPOSALS FOR INITIAL ELECTRON SCATTERING EXPERIMENTS
USING THE SLAC SPECTROMETER FACILITIES

Submitted

By

SLAC-MIT-CIT Collaboration

Particle physicists actively participating in the collaboration at this time:

Stanford Linear Accelerator Center (Group A)

W.K.H. Panofsky, D. H. Coward, H. DeStaebler,
J. Litt, L. W. Mo and R. E. Taylor.

Massachusetts Institute of Technology

J. I. Friedman, H. W. Kendall and L. Van Speybroeck.

California Institute of Technology

C. Peck and J. Pine.

January 1966

SLAC proposal from almost 54 years ago

TABLE OF CONTENTS

We are submitting three proposals:

I. Electron-proton elastic scattering

II. Electron-proton inelastic scattering

III. Comparison of positron-proton and electron-proton elastic scattering.

Measuring <u>both</u> the elastic and the inelastic scattering at high Q^2 was key to SLAC's role in the discovery of quarks

From Michael Riordan's "The discovery of quarks"

Science **256**, 1287 (1992)

- The elastic cross section dropped roughly as the 6th power of Q^2, and the

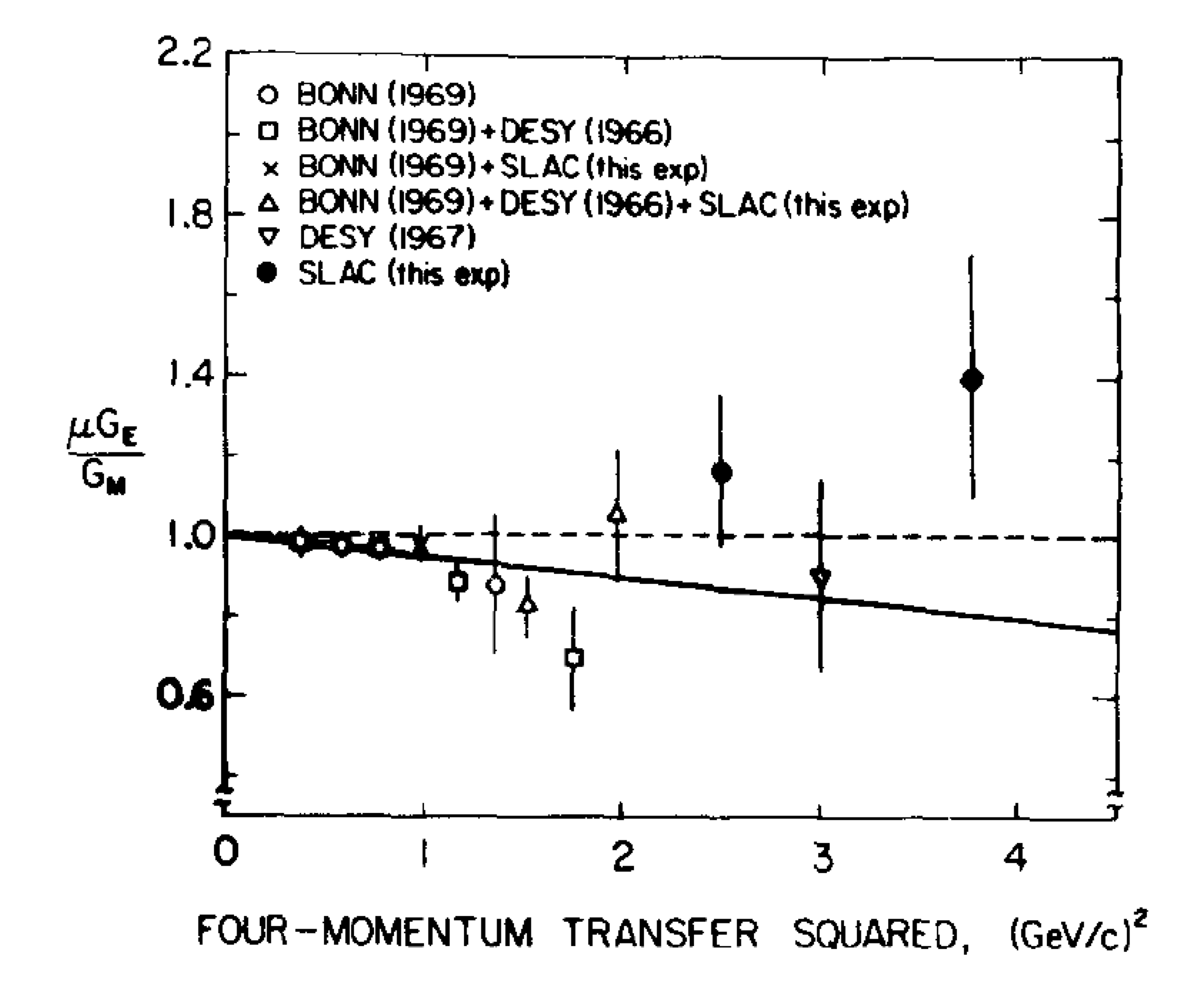
  "… behavior was generally interpreted as evidence for a soft proton lacking any core; it was commonly thought that the existence of such a core would have slowed the rate at which the cross section decreased"

- However, Riordan describes how in the first inelastic experiment, the

  " … raw counting rates were much higher than had been expected in the deep inelastic region"

- " In hindsight, such an observation paralleled the discovery of the atomic nucleus by Ernest Rutherford .. .."

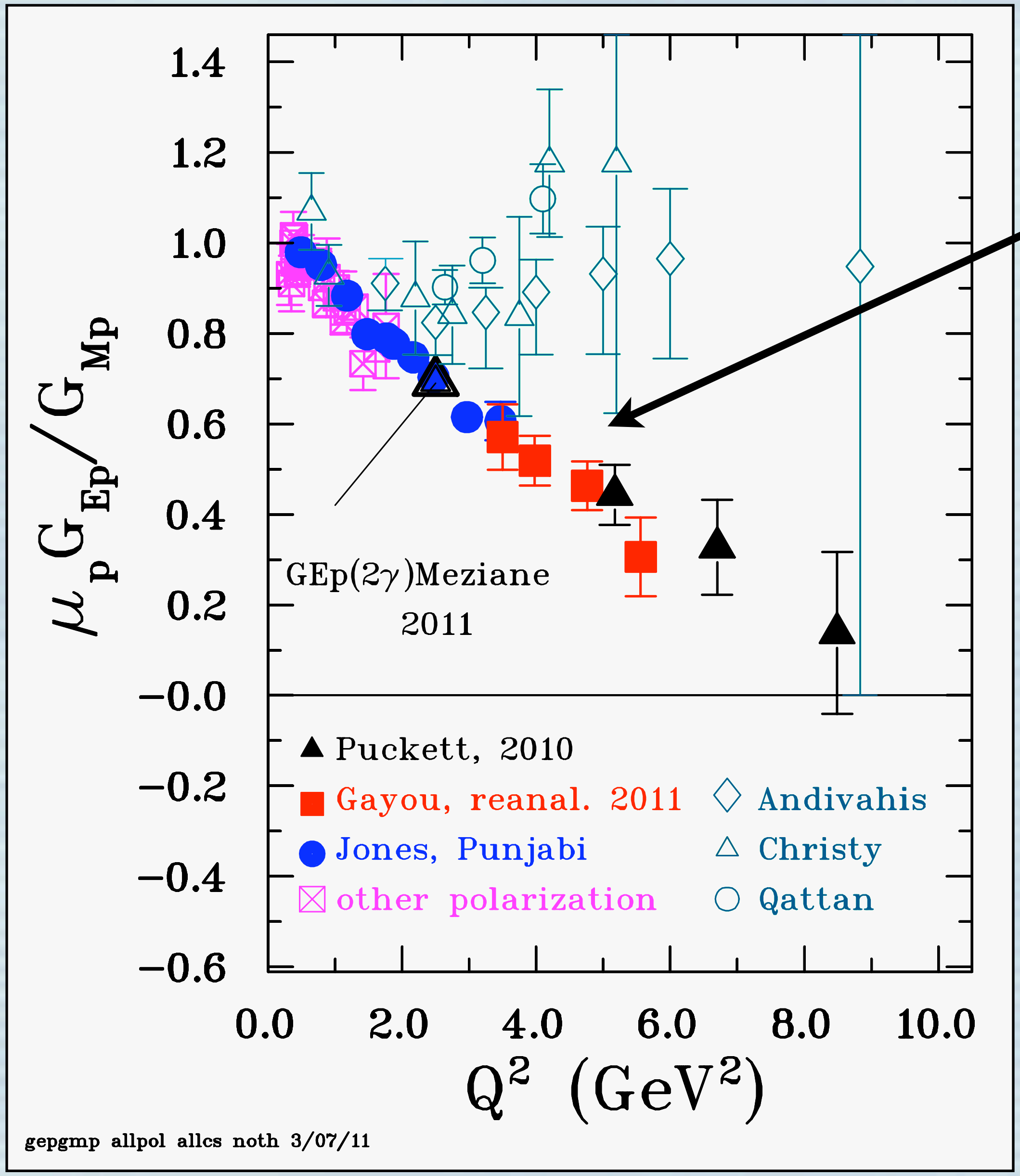
Elastic scattering at SLAC circa 1970 also helped set the stage for big surprises at JLab



Litt et al., Phys. Lett. 31B, 40 (1970)

These data helped start a bias to expect that $\mu_p G_E^p / G_M^p \sim 1$

The measurements of $\mu_p G_E^p/G_M^p$ using the recoil polarization technique at JLab



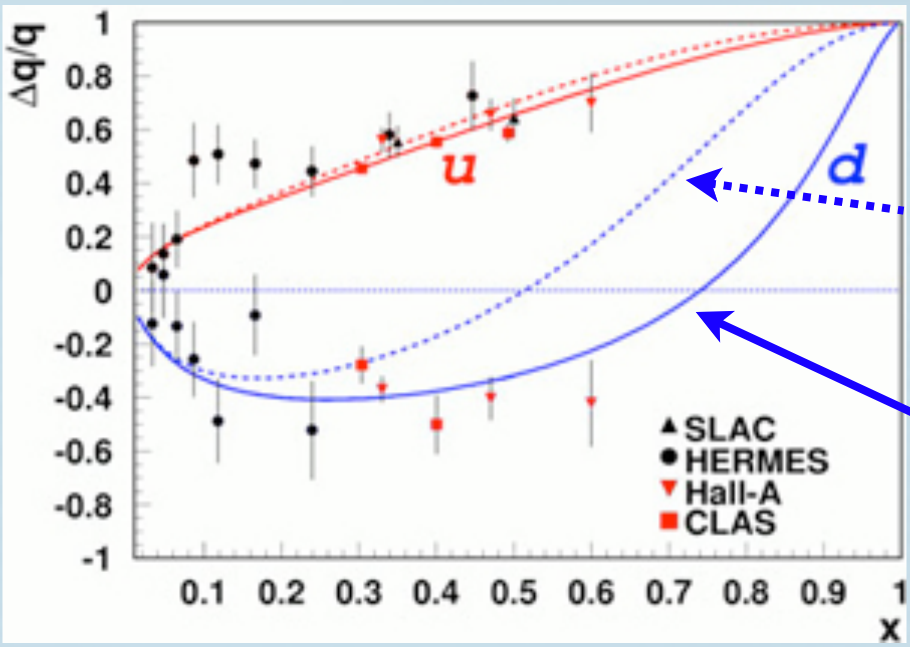
Data from both Rosenbluth separations and the double-polarization technique.

Resulted in the 2017 Bonner Prize in Nuclear Physics being awarded to to Charles Perdrisat of William and Mary

Explanations for the Q^2 behavior of G_E^p/G_M^p have emphasized the role of quark orbital angular momentum.

Evidence for quark orbital angular momentum has subsequently been seen in a variety of other experiments

Deep-inelastic scattering with polarized beam and targets

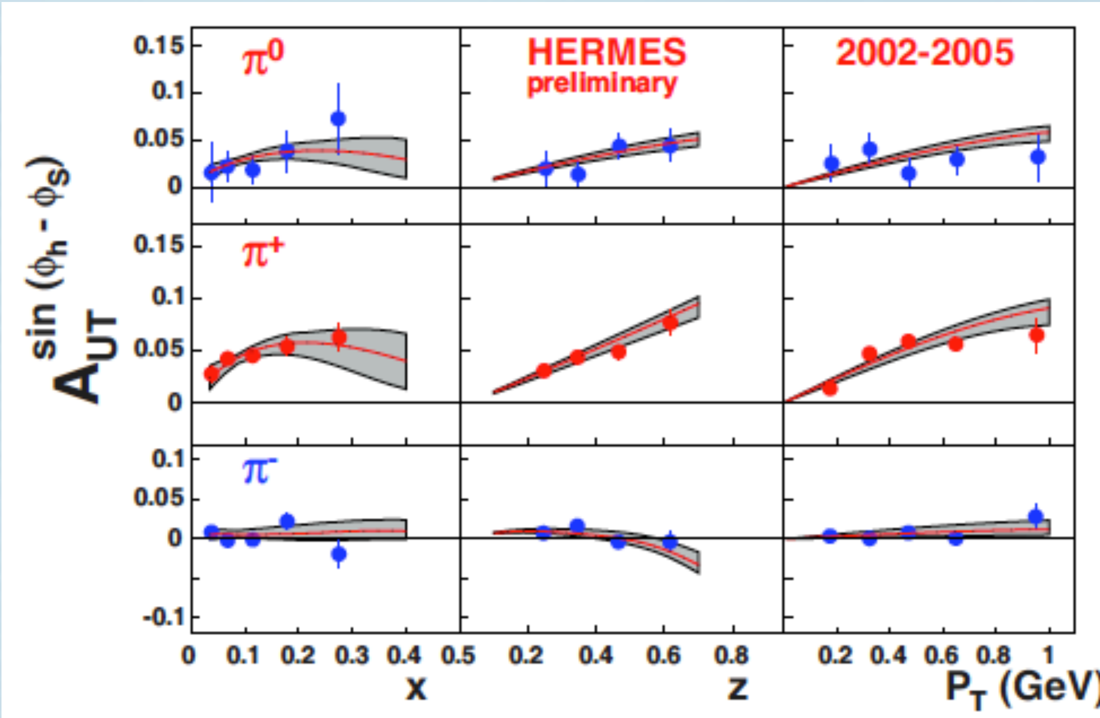


Model without quark orbital angular momentum.

Model with quark orbital angular momentum.

Flavor-separated spin contributions from up and down quarks

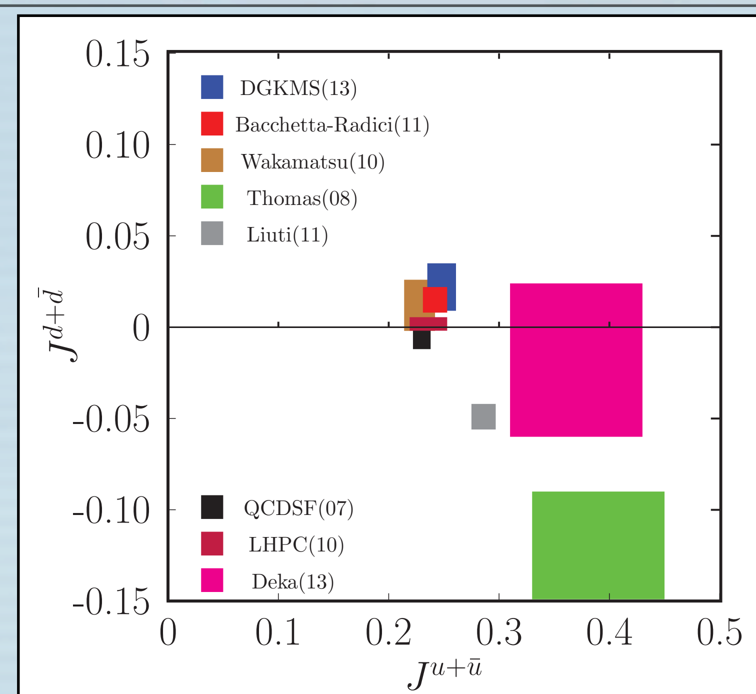
Non-zero Sivers effect in semi-inclusive DIS



GPD models constrained by data from DVCS, DVMP, FF's and more used with the Ji Sum Rule.

$$L^{u+\bar{u}} = -0.146 \ldots -0.172$$

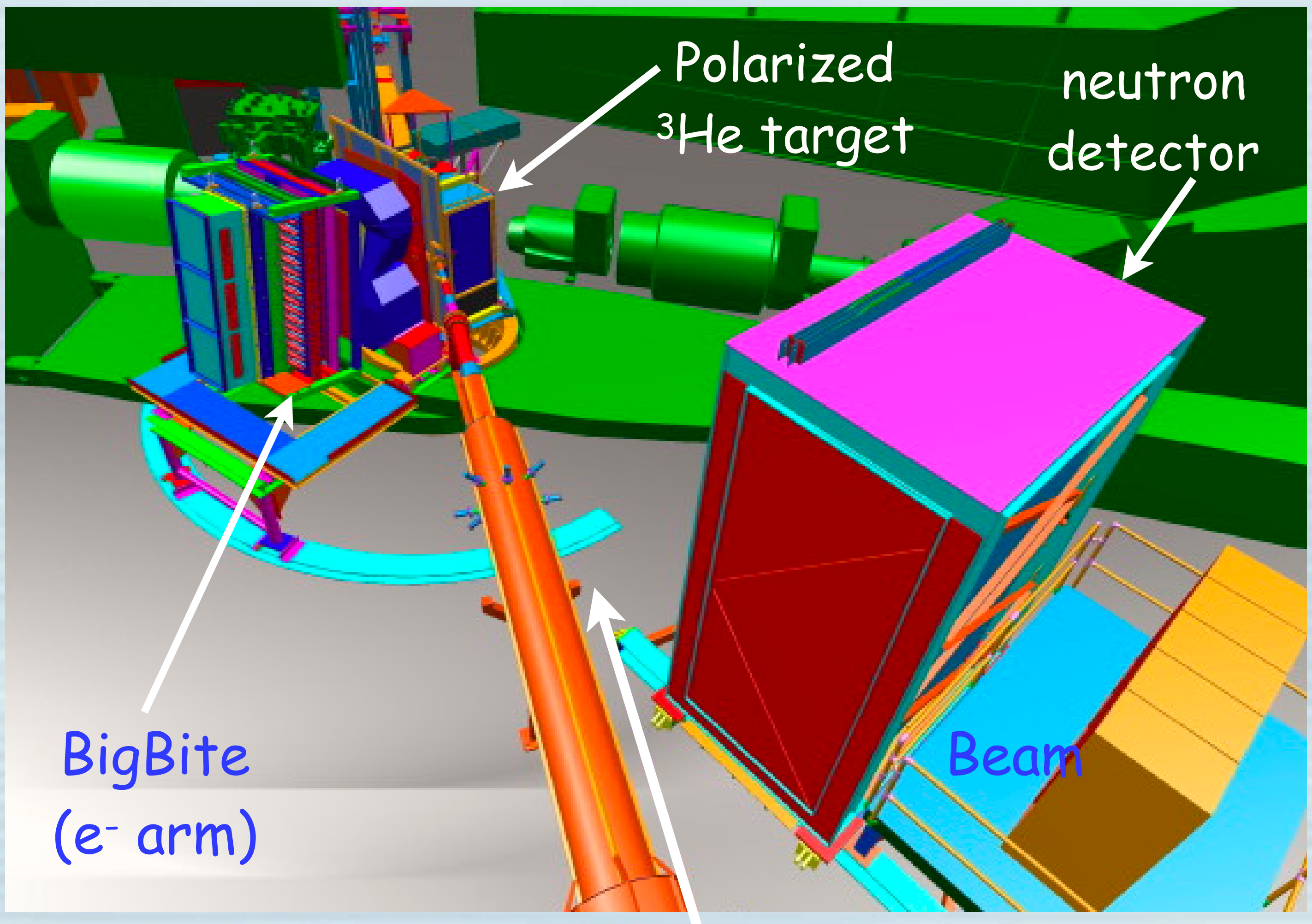
$$L^{d+\bar{d}} = 0.263 \ldots 0.237$$



P. Kroll, EPJ Web of Conferences **85**, 01005 (2015)

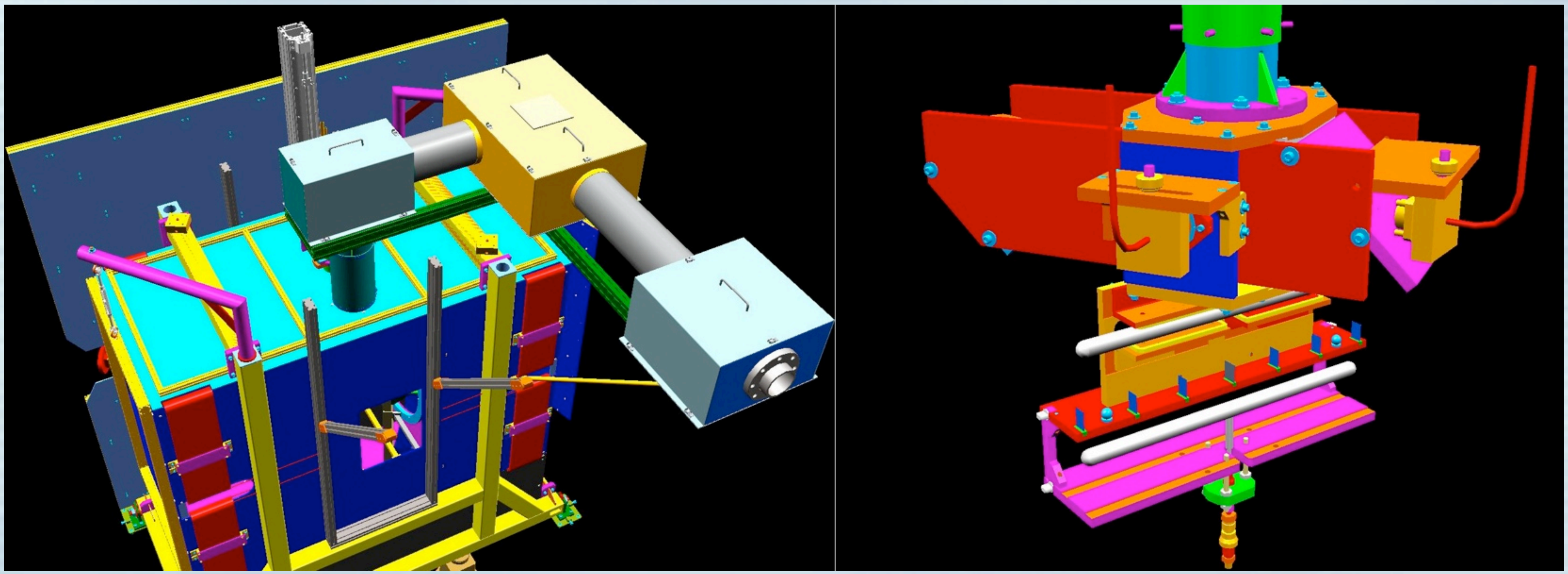
Proton results for G_E/G_M led to keen interest in gaining corresponding results for the **neutron**

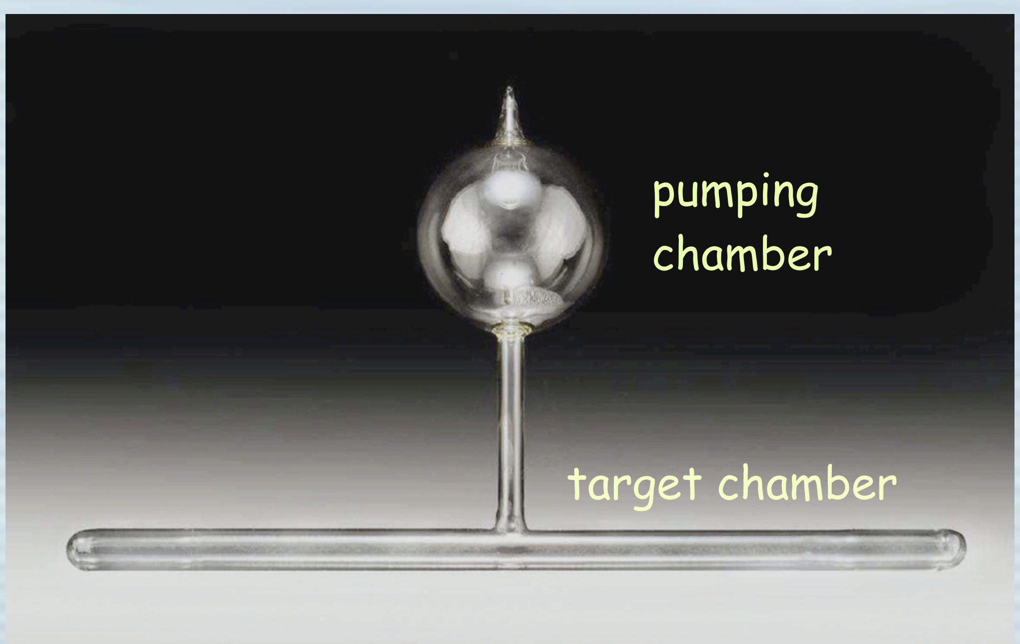
But elastic cross sections at high Q^2 are tiny! To get to a Q^2 comparable with the proton, considerable innovation was needed.



- The experiment measured double-polarization asymmetries in $^3\vec{He}(\vec{e},e'n)pp$
- The electron arm used Big Bite, an open geometry spectrometer using a single dipole, with a detector package that looked directly at the target.
- It also used a high luminosity polarized ^3He target, with a figure of merit more than 10x higher than E142 that measured the neutron spin structure.
- The neutron detector was, I believe the world's largest at that time.

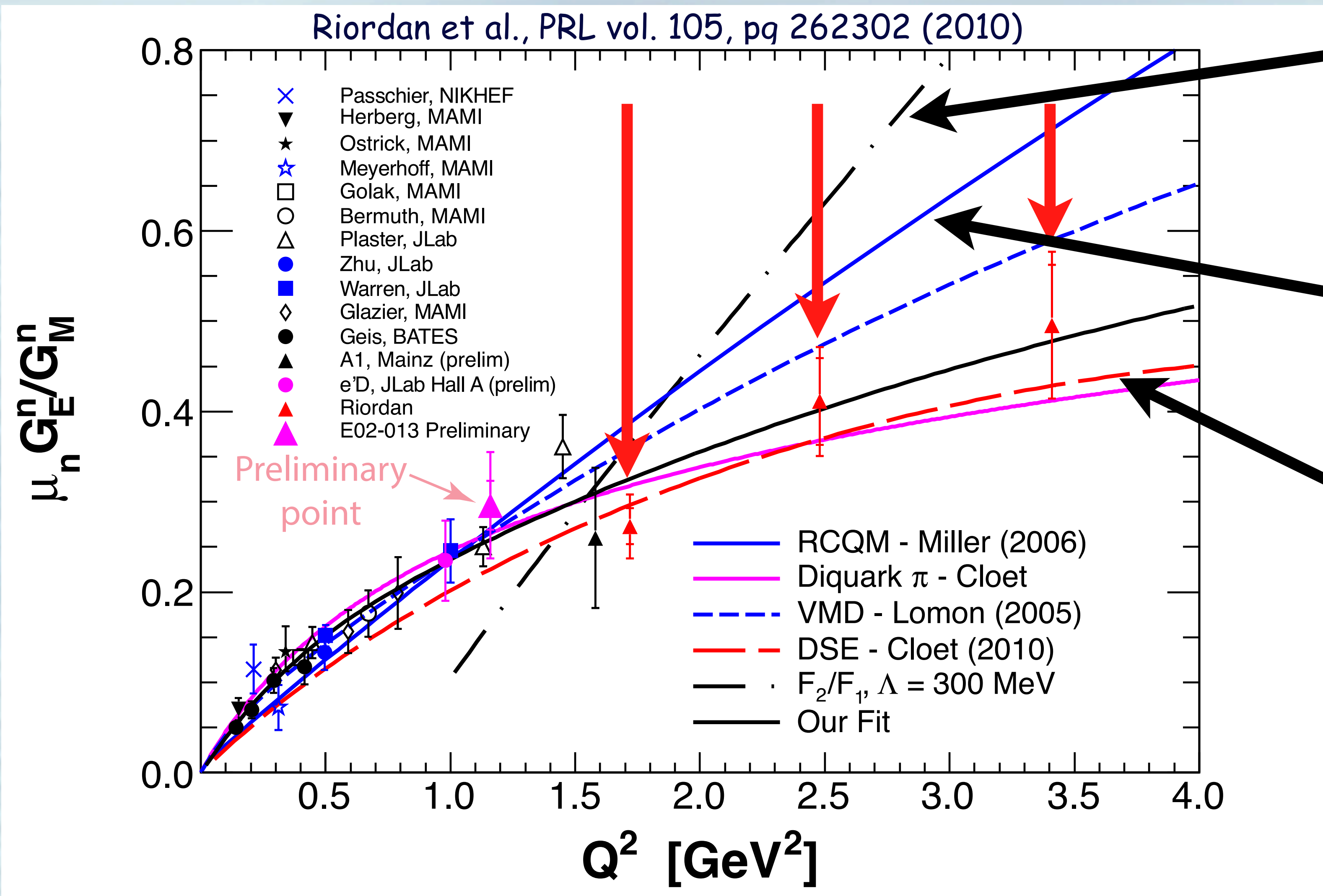
The polarized 3He target for the first precise measurement of G_E^n at high Q^2





- The use of hybrid mixtures of Rb ad K greatly improved the efficiency with which the ^{3}He was polarized.
- Greatly improved commercial high-power diode-laser arrays enabled larger volumes of ^{3}He to be polarized.

Data from the Hall A polarized ^{3}He experiment (E02-013) extended knowledge of G_E^n to high Q^2



Belitsky, Ji and Yuan, logrithmic corrections - 2003

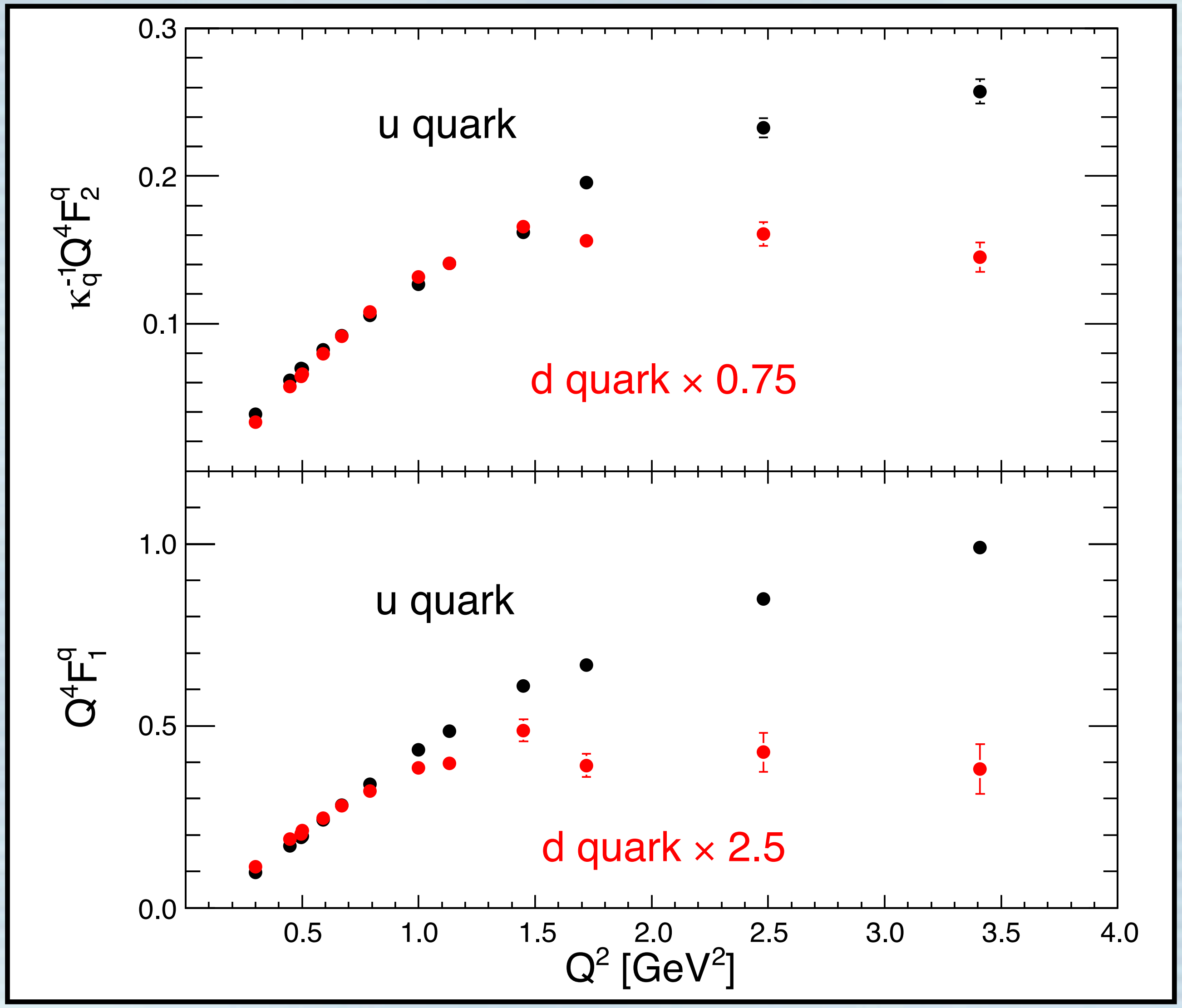
Miller's RCQM - 2002

Cloet, Eichmann, El-Bennich, Kahn and Roberts - DSE/Faddeev - 2009

The BigBite G_E^n experiment provided the first test of theories developed to explain the surprising proton results, although clearly, higher Q^2 would be desirable

With both proton and neutron FF data, one can extract the individual quark contributions

Cates, de Jager, Riordan and Wojtsekhowski, PRL vol. 106, pg 252003 (2011)



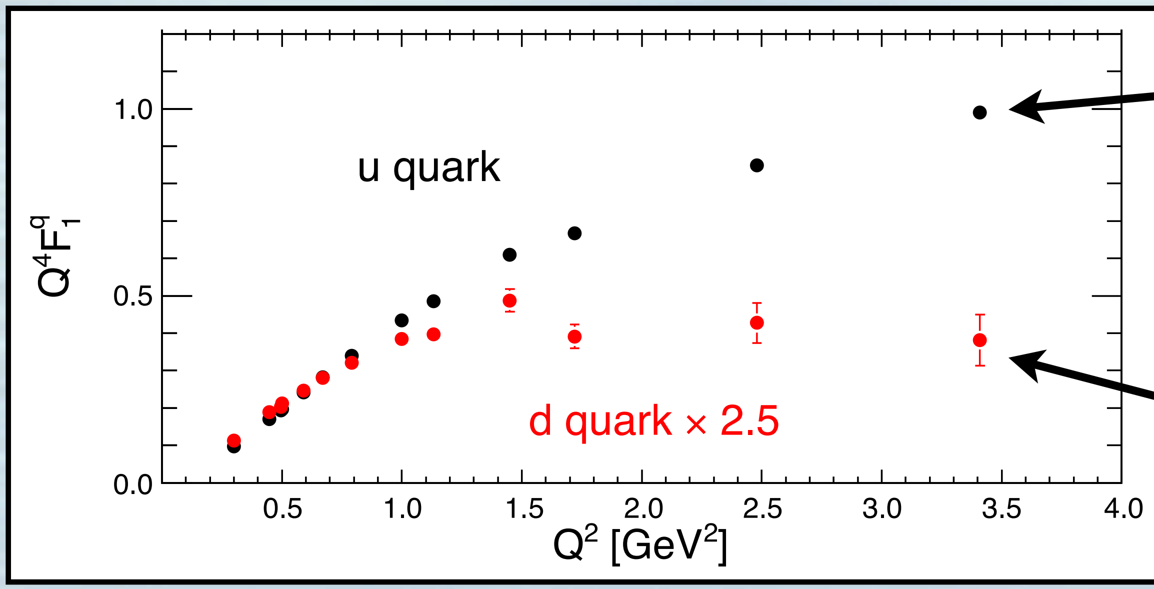
More details on this from Bogdan Wojtsekhowski tomorrow.

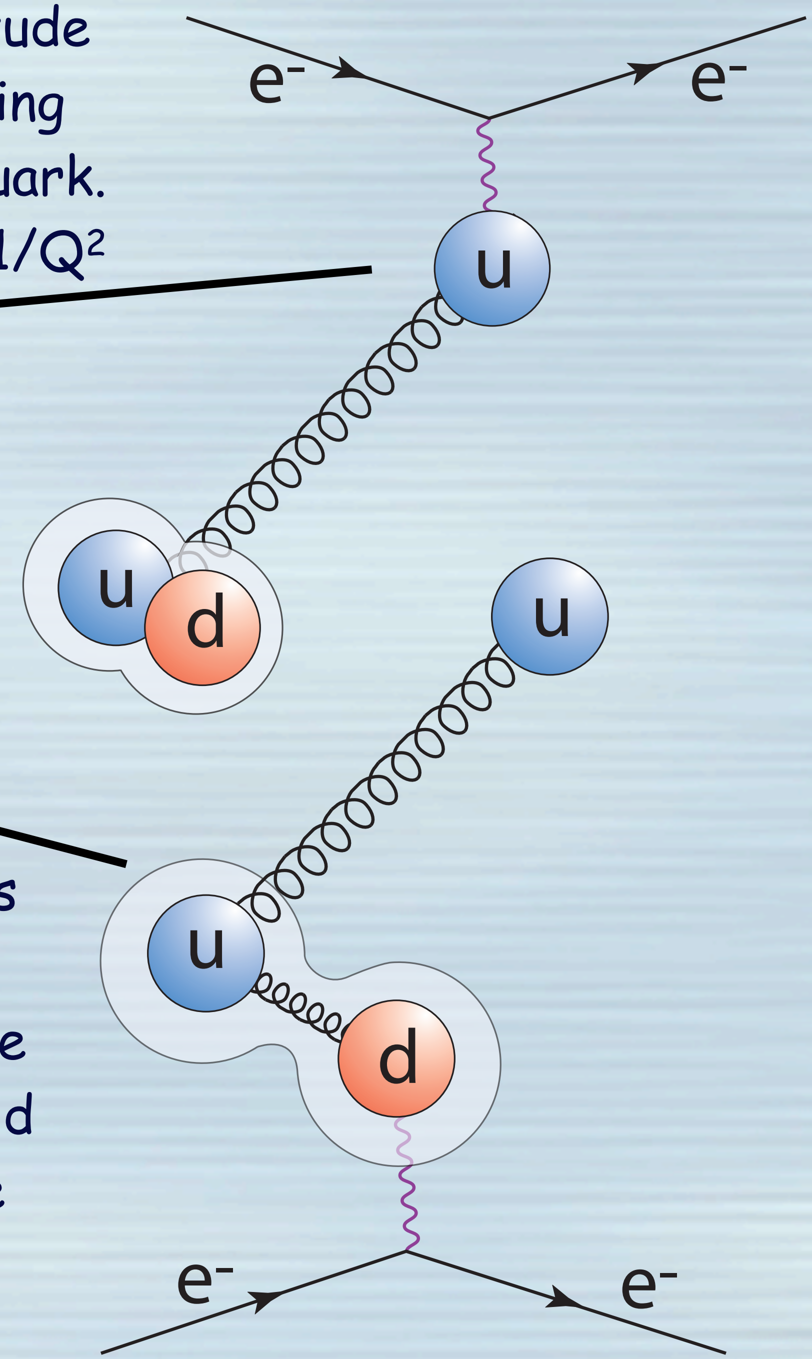
$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \quad \text{and} \quad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

Multiple theoretical models suggest that the different behavior of the u- and d-quarks are indicative of the importance of diquark correlations.

A naive scaling argument suggested by Jerry Miller invokes diquarks

u-quark scattering amplitude is dominated by scattering from the lone “outside” quark. Two constituents implies $1/Q^2$





d-quark scattering amplitude is necessarily probing inside the diquark. Two gluons need to be exchanged (or the diquark would fall apart), so scaling goes like $1/Q^4$

While at present this idea is at the conceptual stage, it is an intriguingly simple interpretation for the very different behaviors, and dovetails nicely into the outstanding question of missing states in the N* spectrum.

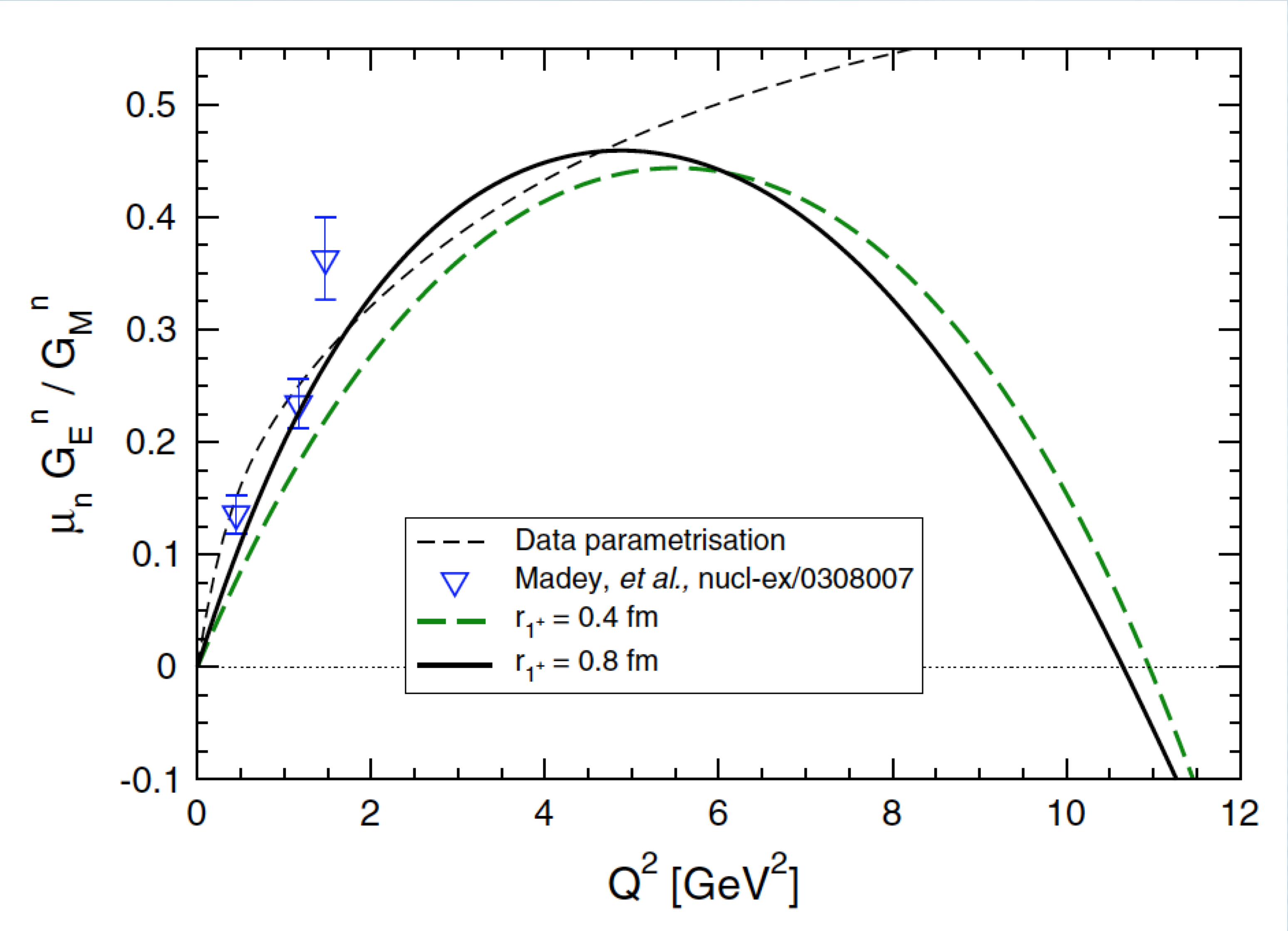
So why measure the nucleon FF's to even higher Q^2

There are many reasons, among them they…

- … will provide exquisite discrimination between different models and approximate forms of QCD.
- … will provide a necessary ingredient in formulating 3-D tomography of the nucleon within the framework of GPDs.
- … will elucidate high-Q^2 behavior (such as scaling) that can be compared with expectations from QCD.
- … enable the determination of the separate behavior of the up- and down-quark contributions in a new regime of Q^2

In short, they could provide a key element of a paradigm shift in how we think about nucleon structure

DSE/Faddeev calculation of $\mu_n G_E^n/G_M^n$



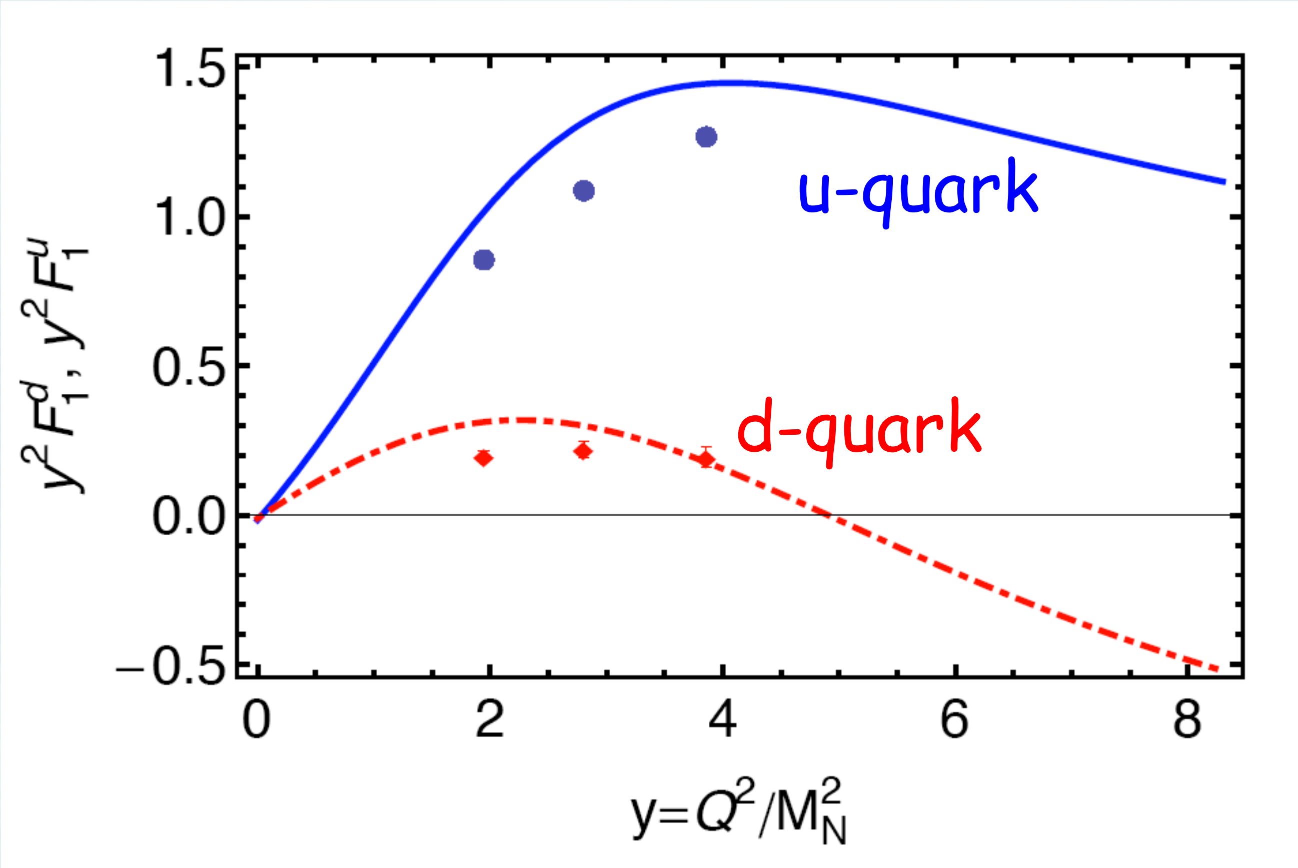
Cloet, Eichmann, El-Bennich, Kahn and Roberts, Few-Body Systems 46, 1-36 (2009)

Many of the theoretical models that reproduce the above trends indicate the importance of diquark correlations.

DSE/Faddeev calculation of $Q^4F_1^u$ and $Q^4F_1^d$

Cloët, Roberts and Wilson, using the QCD DSE approach, have made:

" ... a prediction for the Q^2-dependence of u- and d-quark Dirac and Pauli form factors in the proton, which exposes the critical role played by diquark correlations within the nucleon."



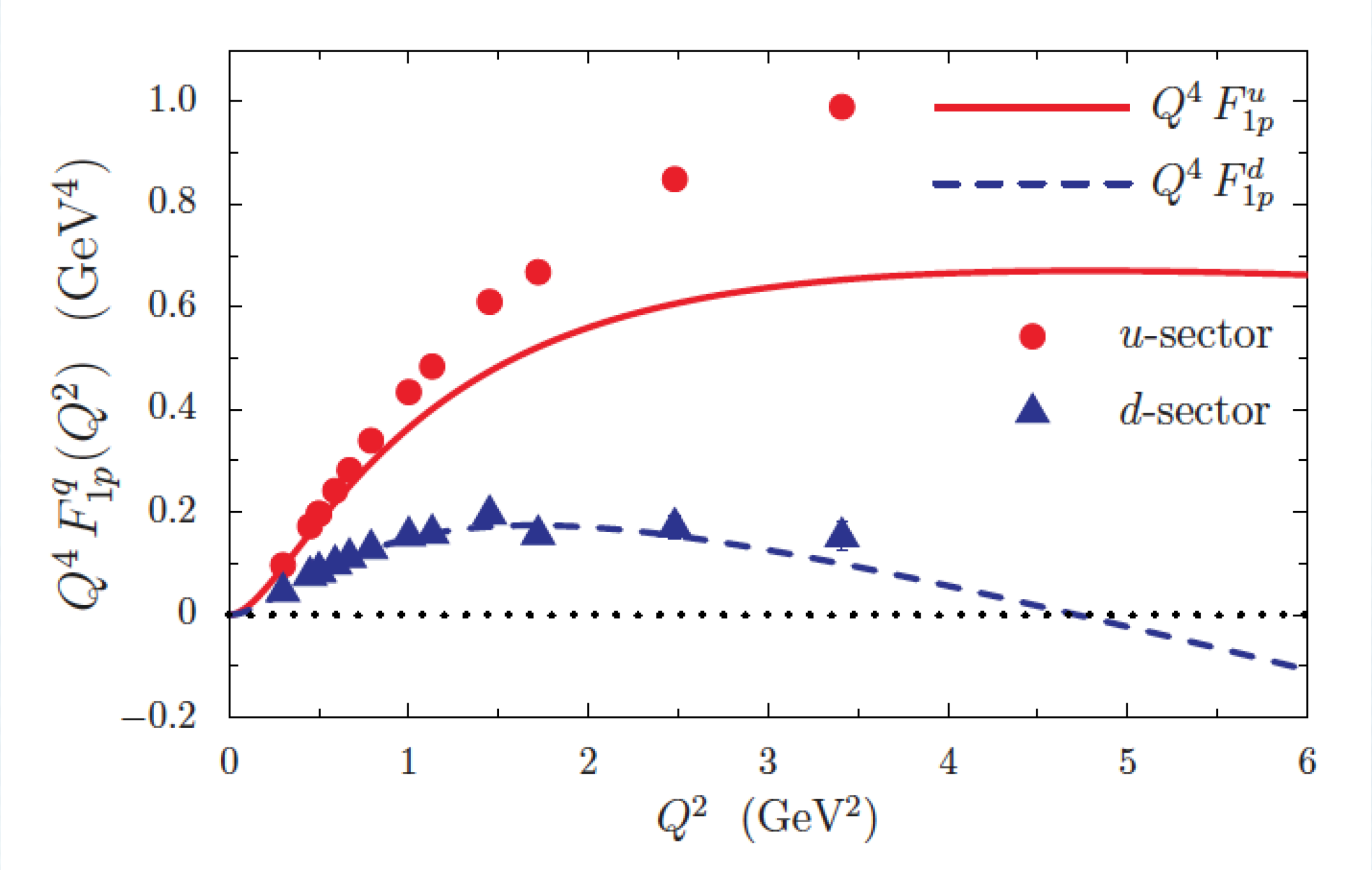
arXiv:1103.2432v1

Within their model, the different behaviors of the u- and d-quark FFs are a direct consequence of diquark degrees of freedom.

Nambu-Jona-Lasinio model

Cloet, Bentz and Thomas

PHYSICAL REVIEW C **90**, 045202 (2014)



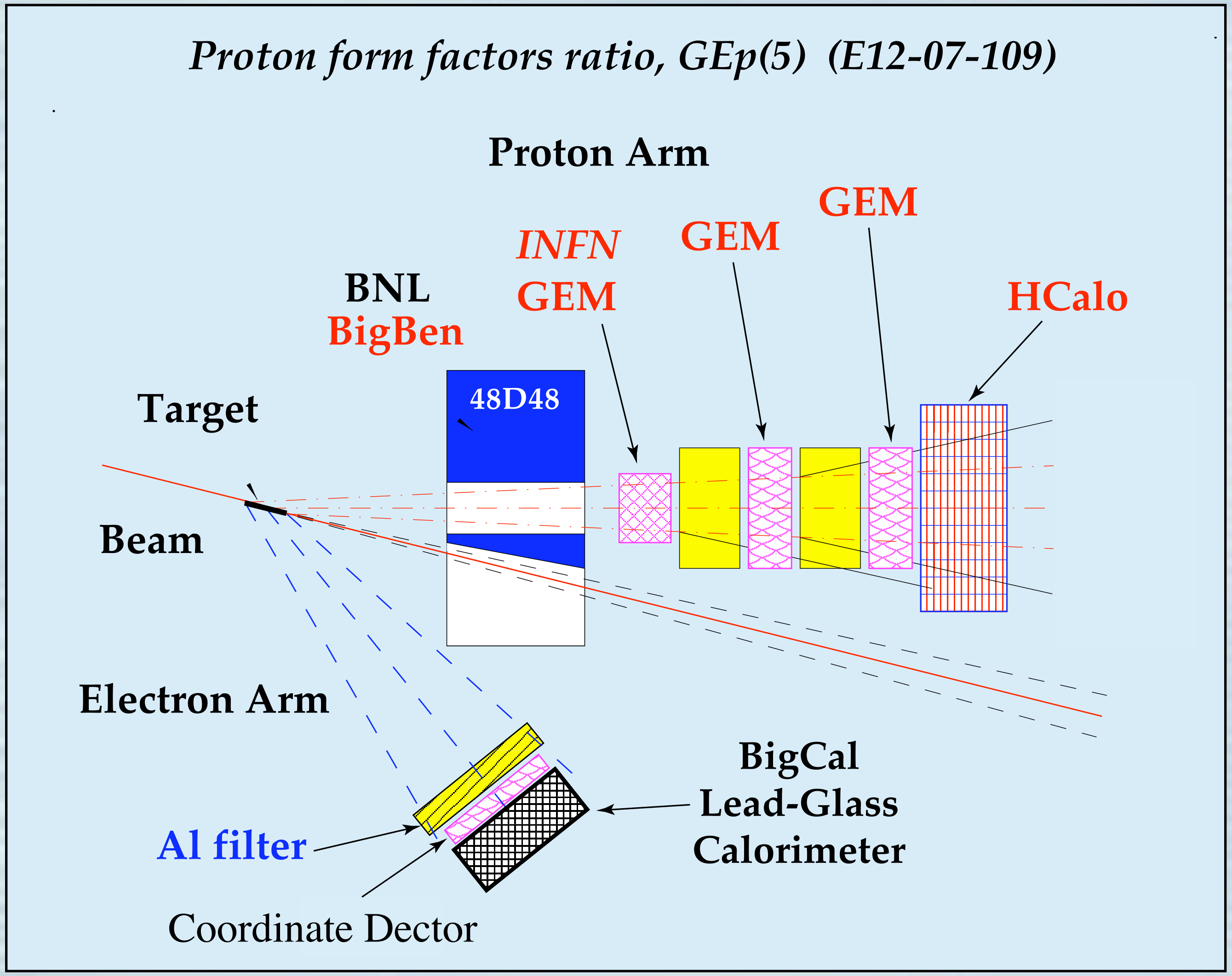
Again, the importance of scalar diquark correlations causes distinctly different behavior for the u- and d-quark sectors

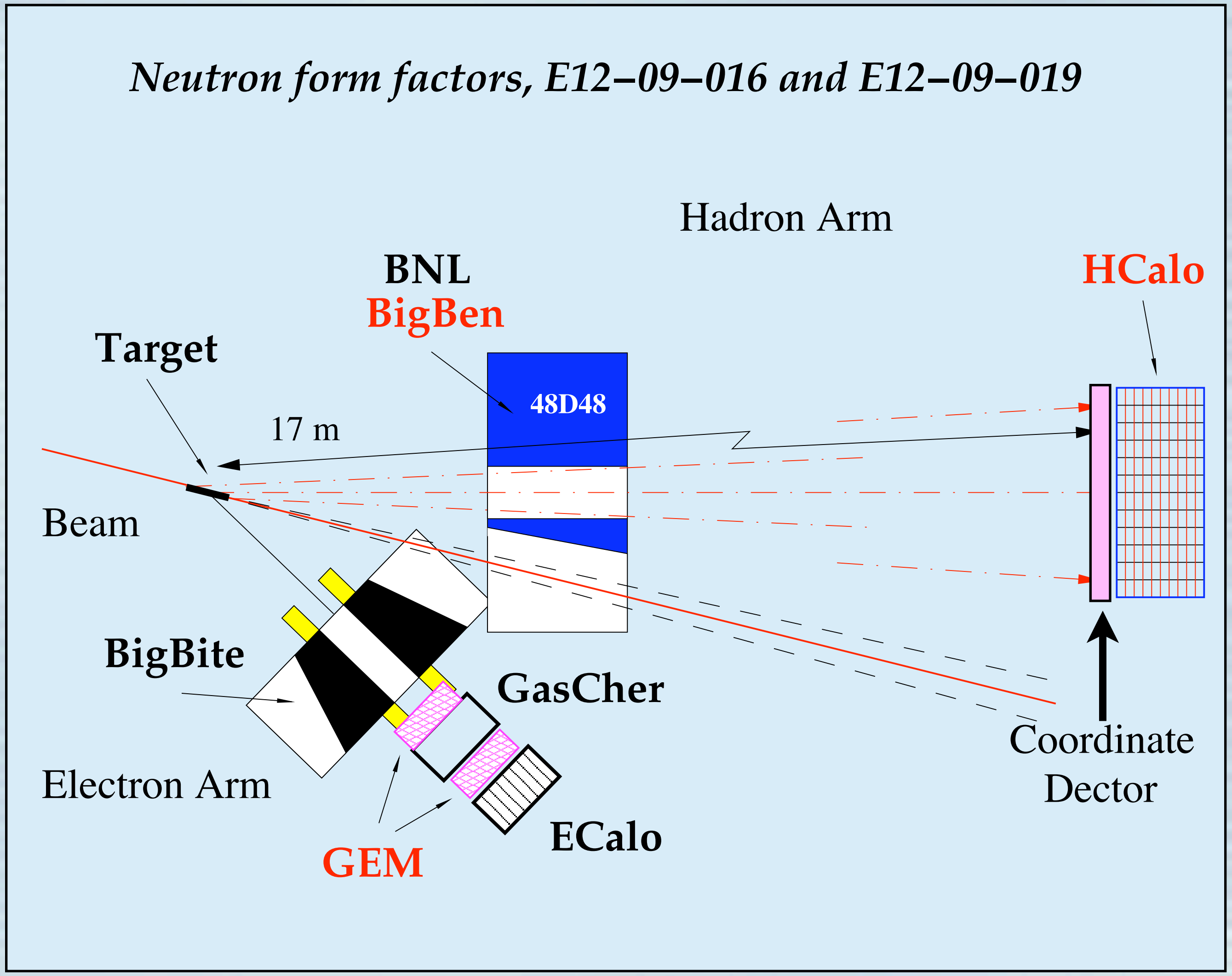
Next, <u>how</u> to measure the nucleon FF's at high Q^2

The Super Bigbite Spectrometer

In essence, SBS takes the open-geometry approach successfully applied in the first polarized ^3He G_E^n measurement using BigBite, and extends the approach.

The SBS equipment will be configured differently depending on the experiment





G_E^p/G_M^p

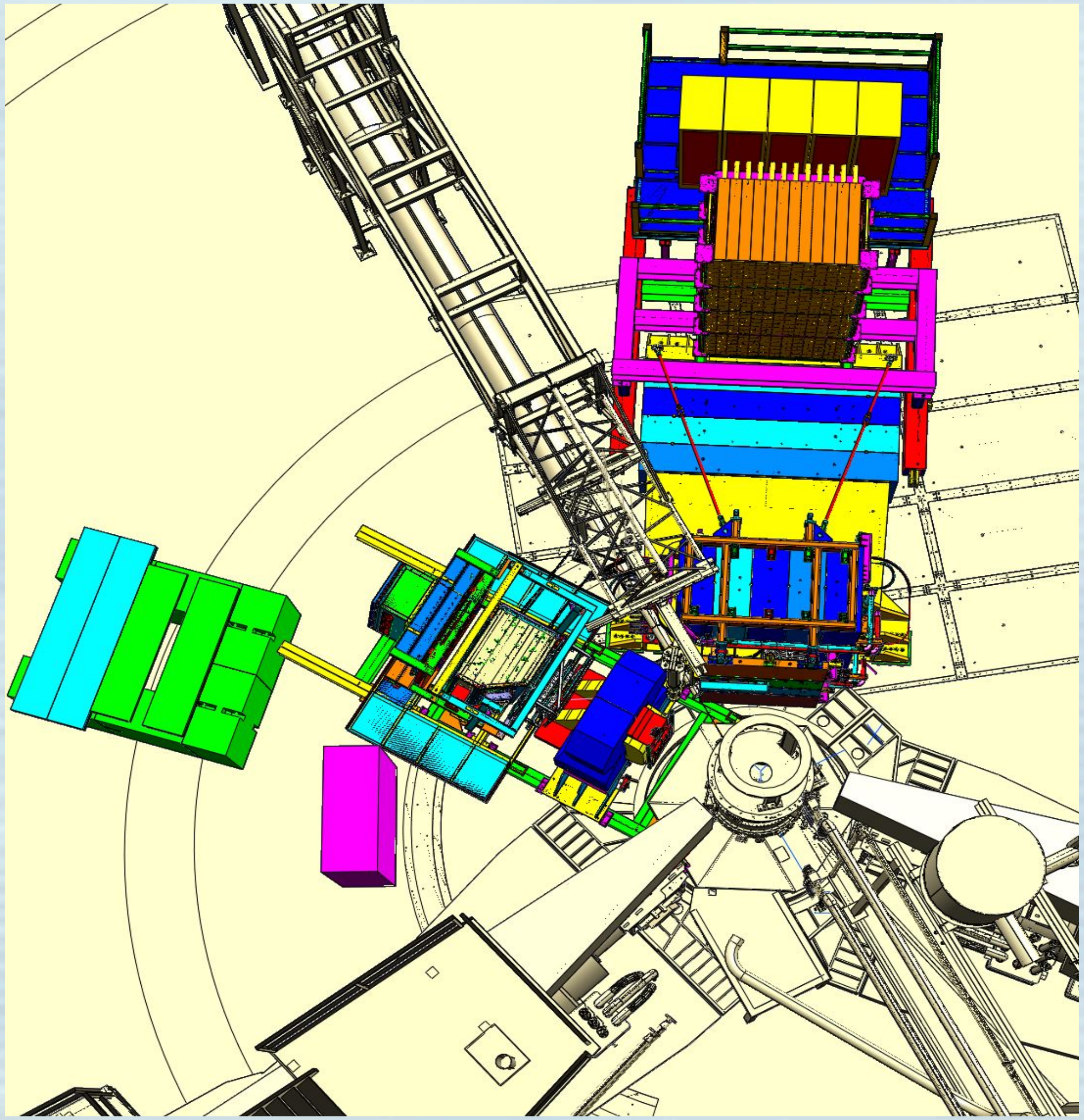
G_E^n/G_M^n and G_M^n/G_M^p

The first SBS experiments and their likely order:

- E12-09-019: measurement of G_M^n/G_M^p to Q^2=13.5 GeV^2.
  Installation will probably begin in May of 2020
- E12-17-004 measurement of G_E^n/G_M^n at Q^2=4.5 GeV
- E12-09-016: measurement of G_E^n/G_M^n to Q^2=10 GeV^2.
- E12-07-109: measurement of G_E^p/G_M^p to Q^2=12 GeV^2.

Super Bigbite will provide game-changing capability to study the elastic nucleon form factors at very high momentum transfer.

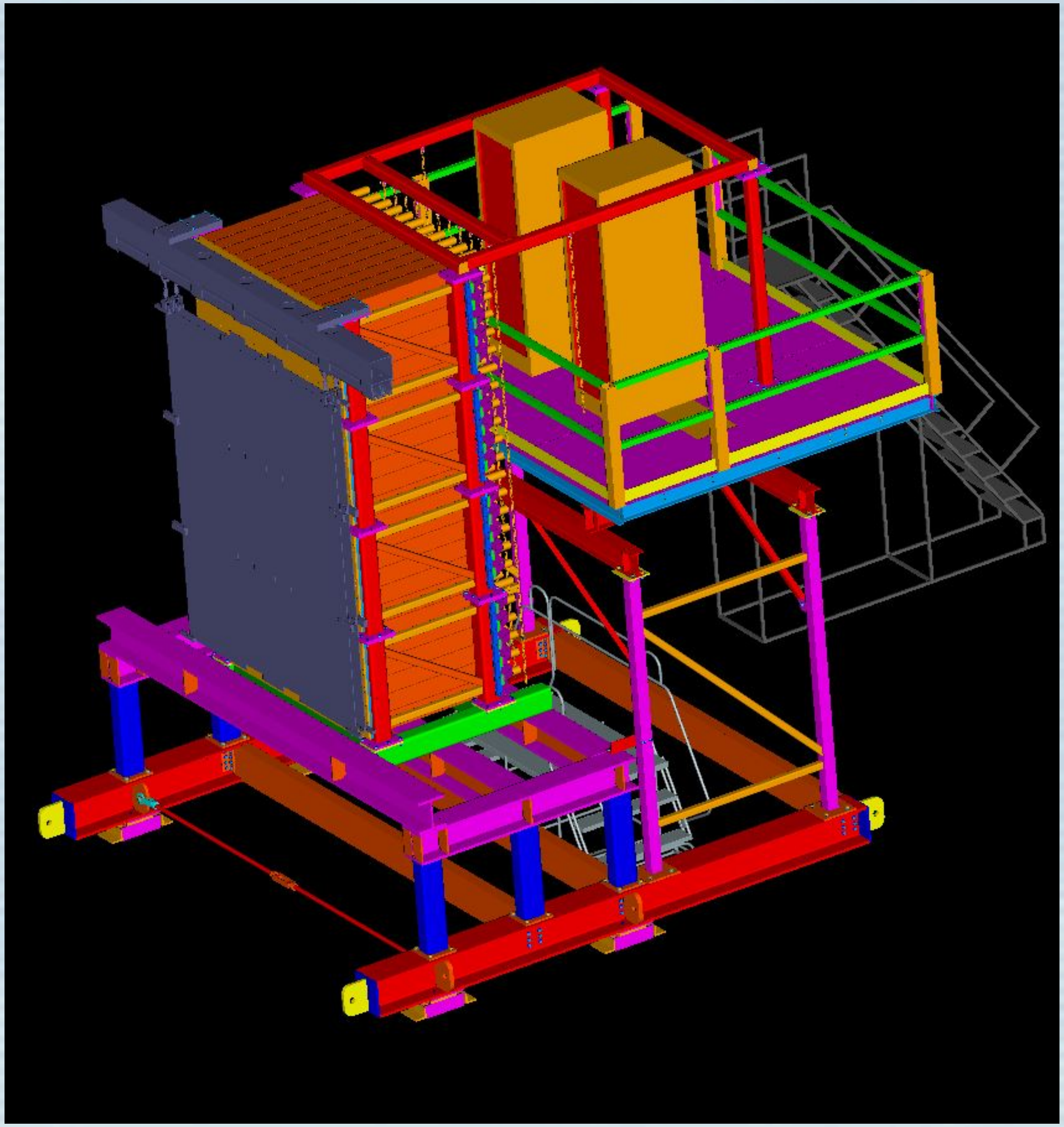
The **first** SBS experiment: measurement of the ratio G_M^n/G_M^p: E12-09-019



- Electron arm will use BigBite w/ upgraded detector package utilizing GEMs.
- Neutron arm will use the SBS magnet to deflect protons relative to neutrons along with a hadron calorimeter, HCal.
- The set-up is very similar to what will be used to measure G_E^n using polarized ^3He.
- Complementary to CLAS12 G_M^n measurement with different and smaller systematics

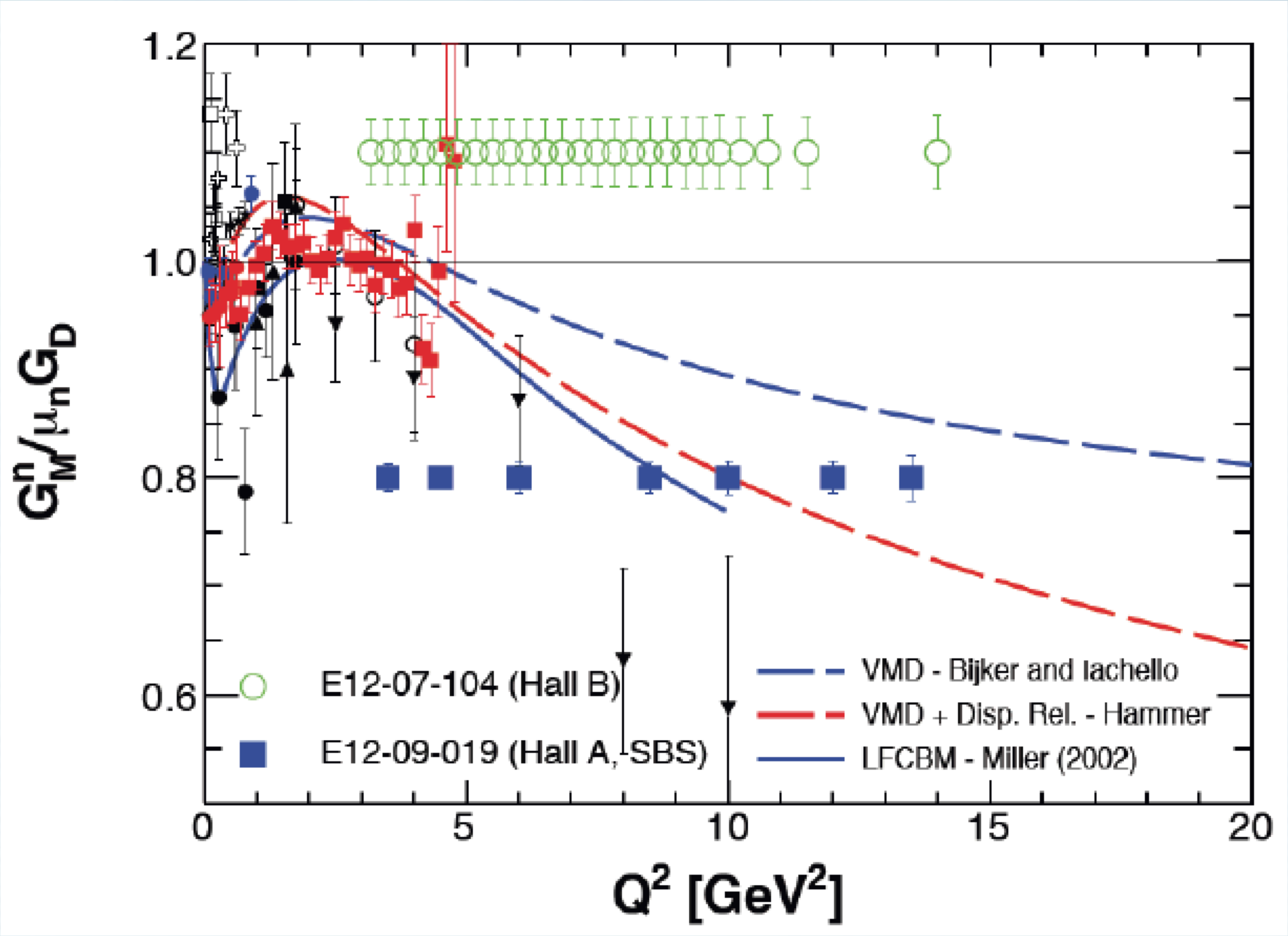
HCal - will be used in all four experiments form-factor experiments

- Hadron calorimeter has ~700 ps ToF accuracy and 30% energy resolution.
- 288 modules 3.6x1.8 m for acceptance matching at 17m
- >95% neutron and proton detection efficiency with near total suppression of all low-energy background < 1 GeV

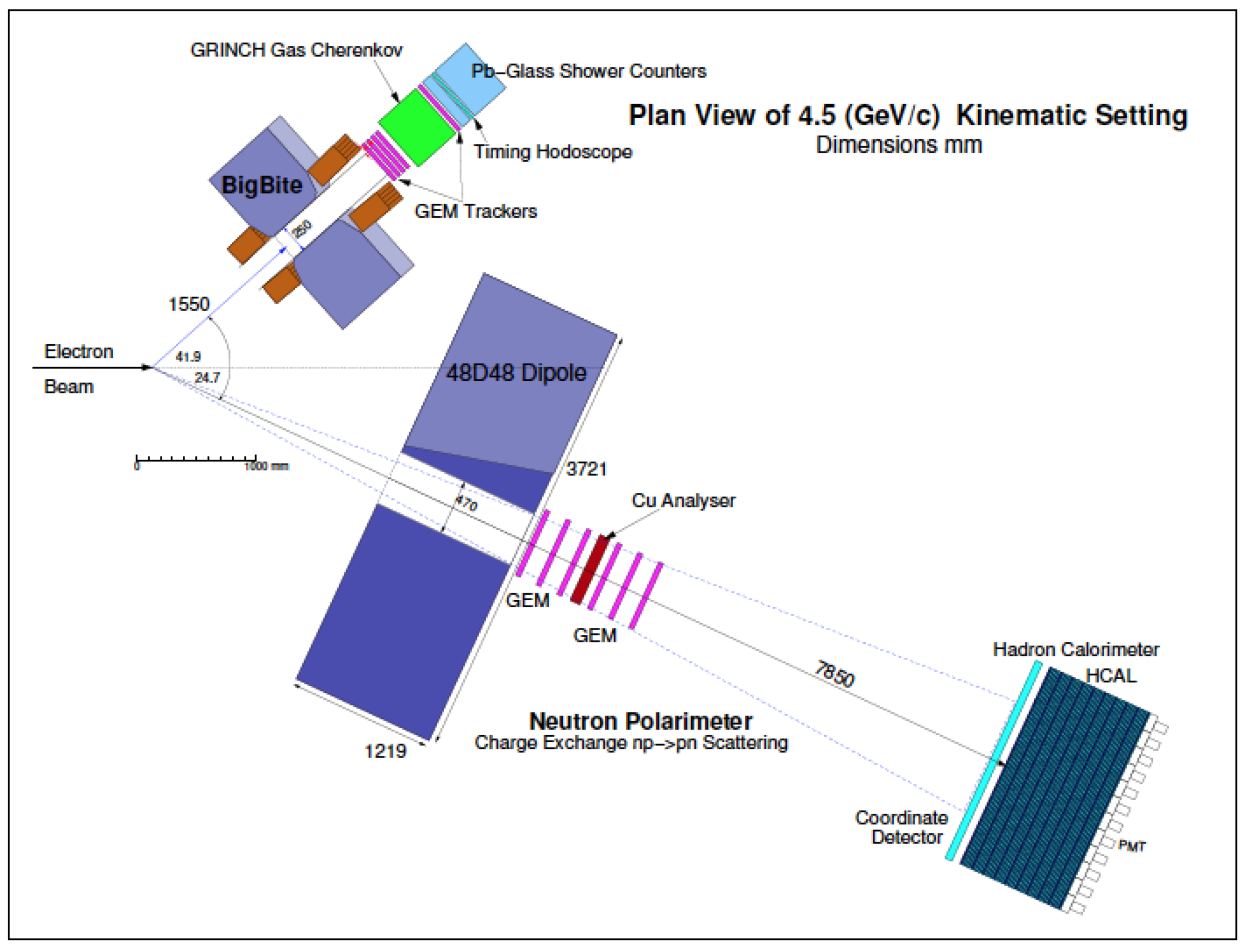


The **first** SBS experiment: measurement of the ratio G_M^n/G_M^p:

E12-09-019

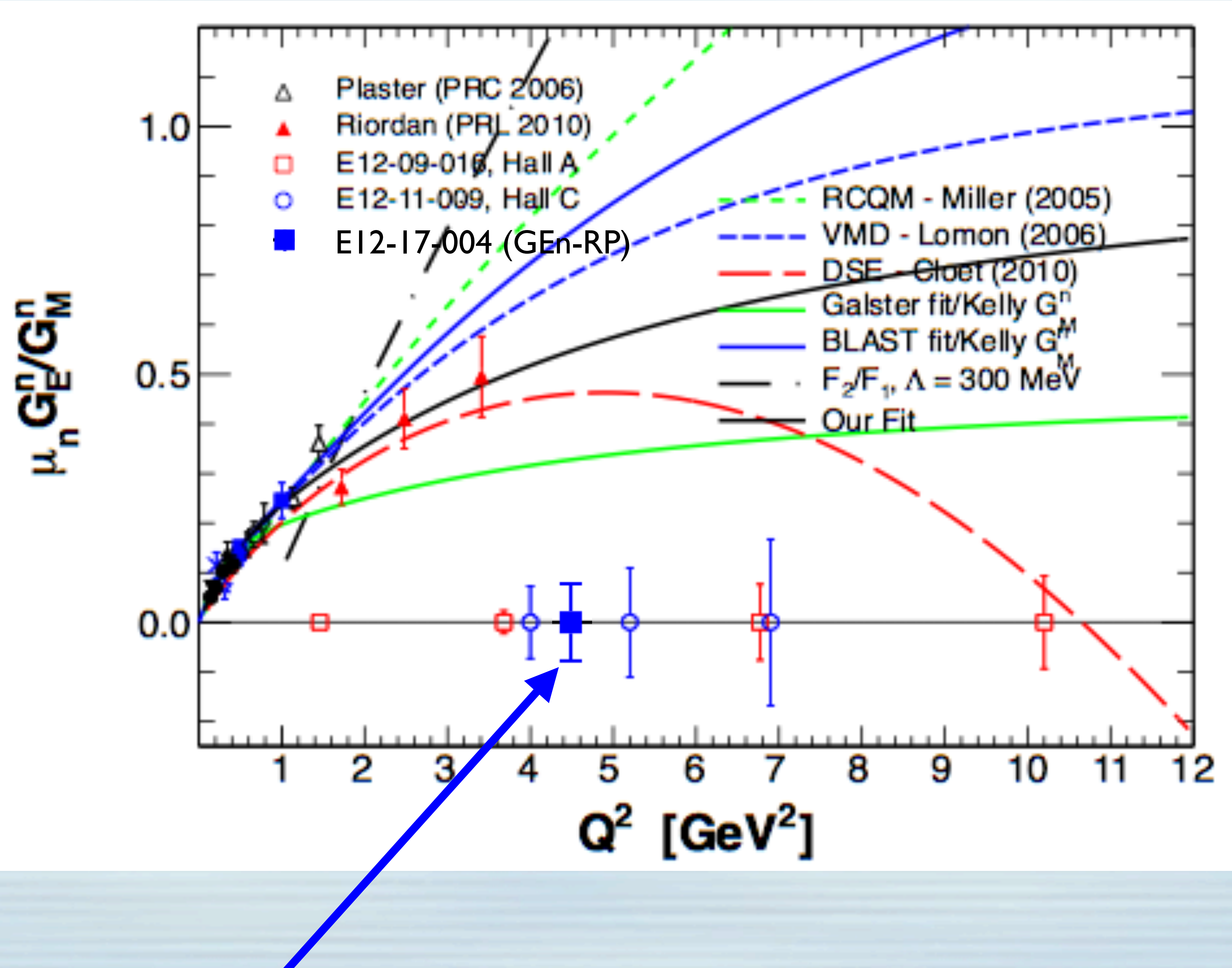


The <u>second</u> SBS experiment, the G_E^n-Recoil Polarimeter experiment: E12-17-004



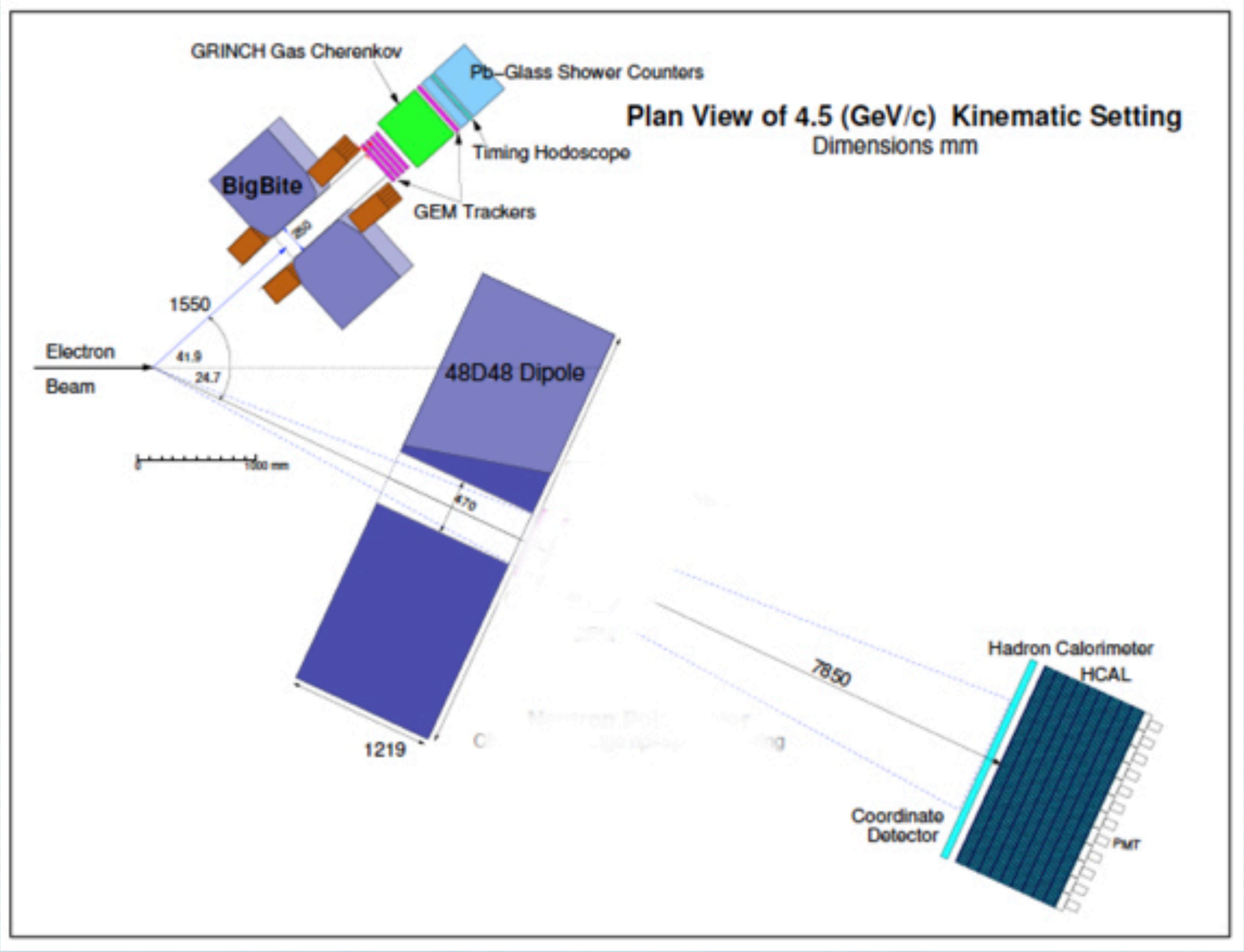
- Will run (almost) parasitically with the G_M^n/G_M^p experiment.
- Will use a copper analyzer just after the 48D48 Dipole, taking advantage of new data from Dubna.
- Will require only ~100 additional hours running
- Will provide highest existing Q^2 point for G_E^n/G_M^p!
- Will also provide additional data on analyzing power which will guide potential future experiments.

The SBS G_E^n-Recoil Polarimeter experiment: E12-17-004



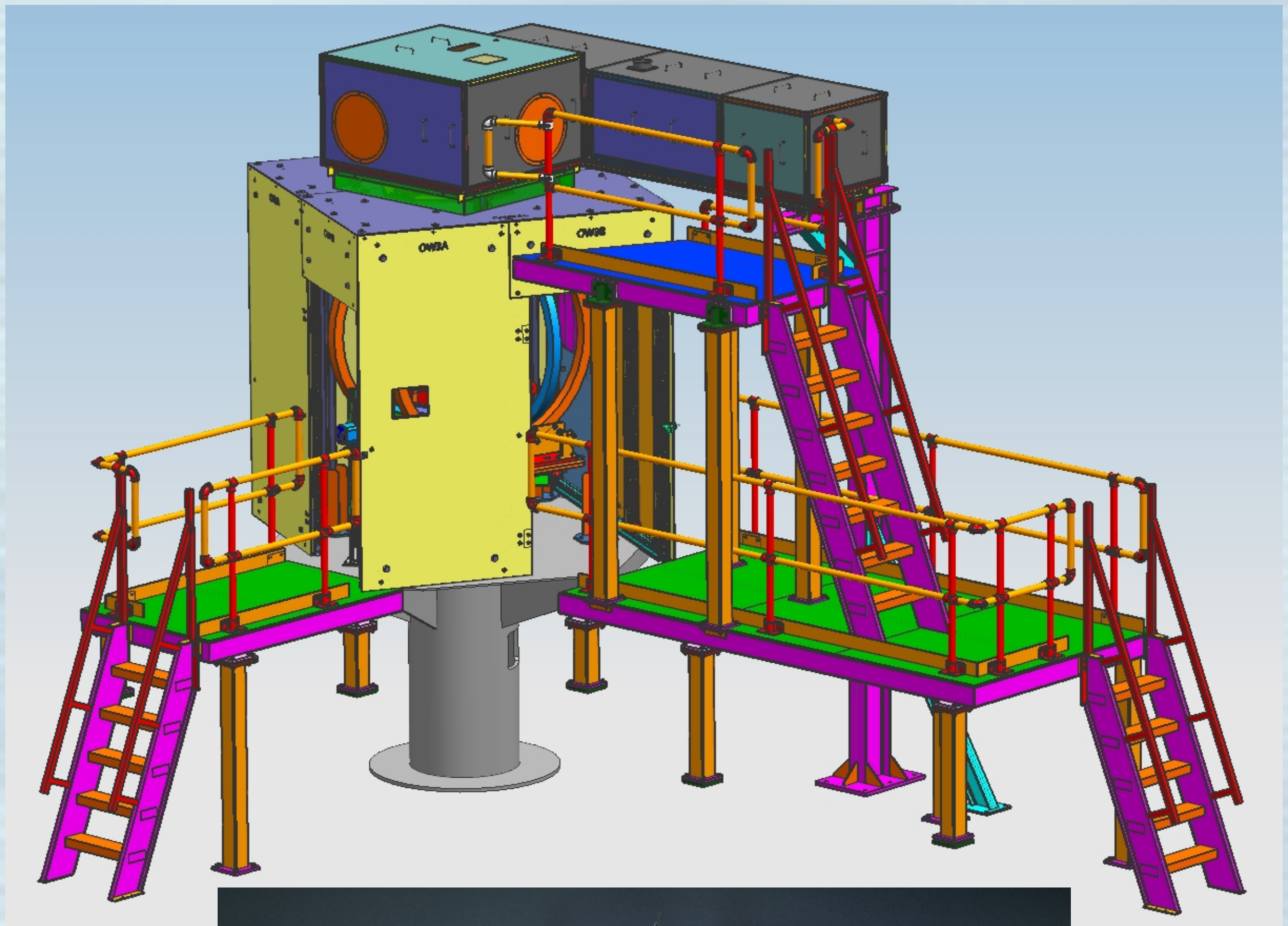
Blue arrow indicates the recoil-polarimeter point

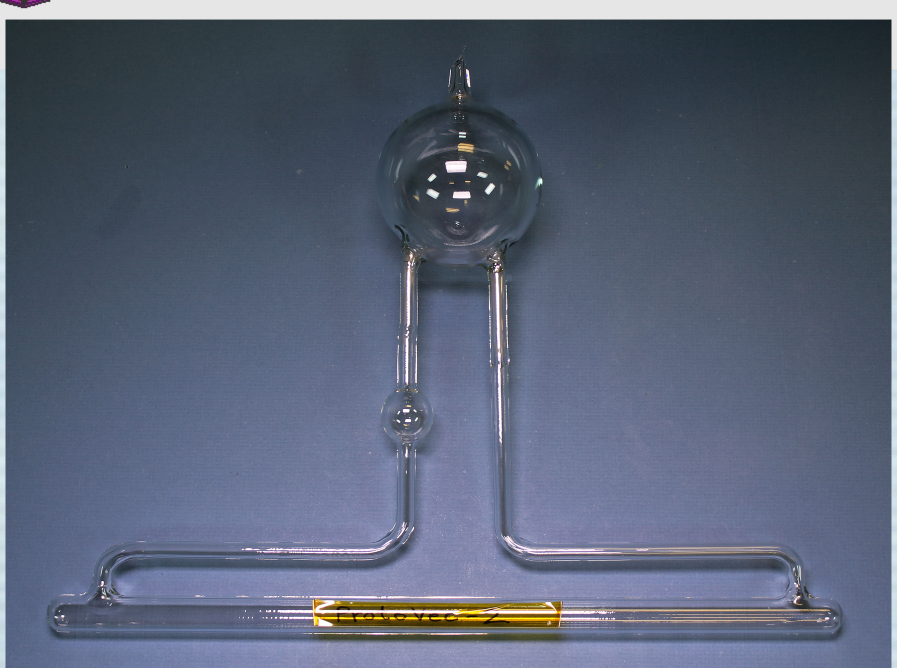
The <u>third</u> SBS experiment, the polarized ^{3}He G_E^n experiment: E12-09-016



- Will use Bigbite upgraded with GEMs for the electron arm.
- Will use the SBS magnet and the hadron calorimeter for the neutron arm.
- Will use a very-high luminosity polarized ^{3}He target.

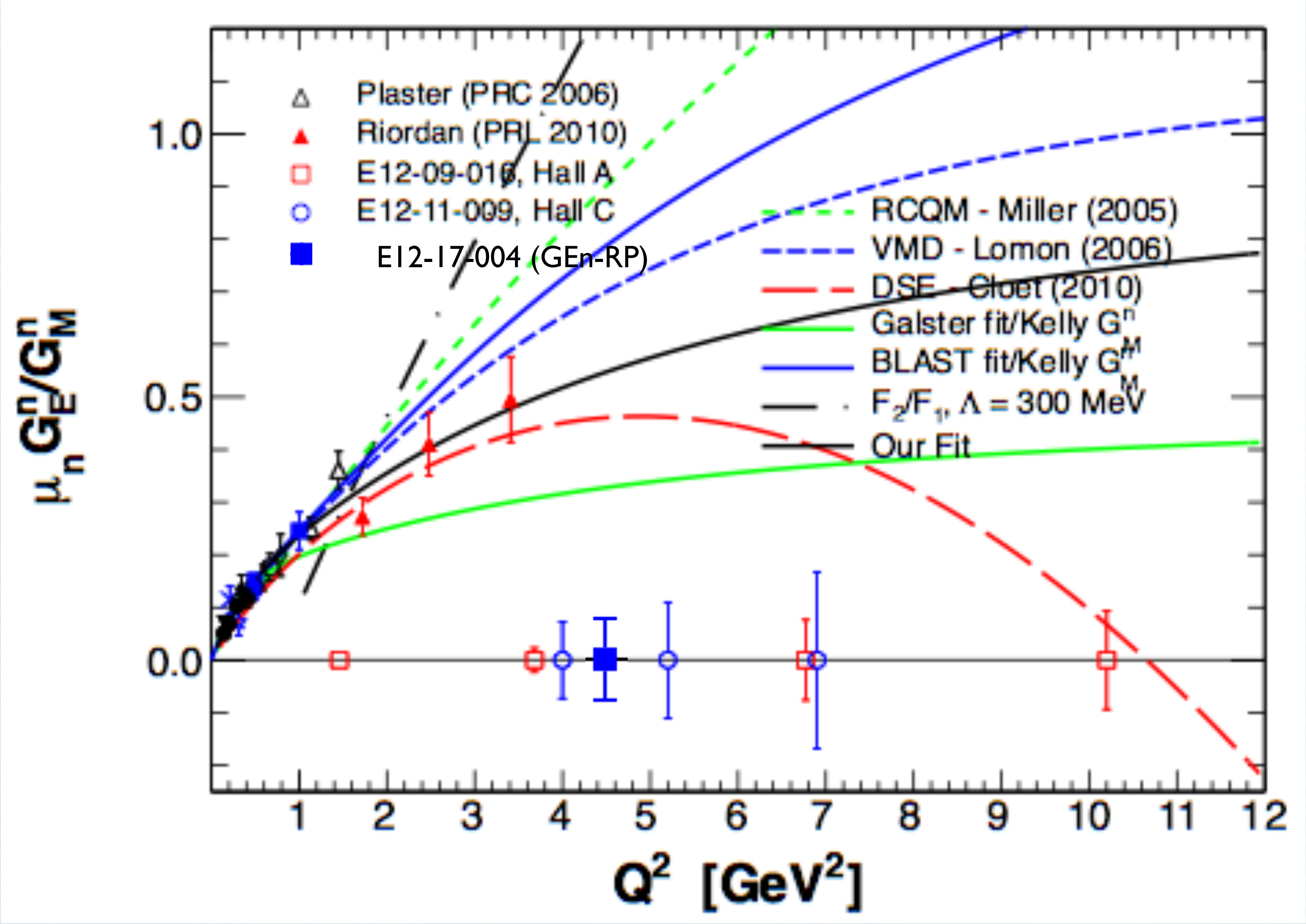
The SBS polarized ^{3}He target





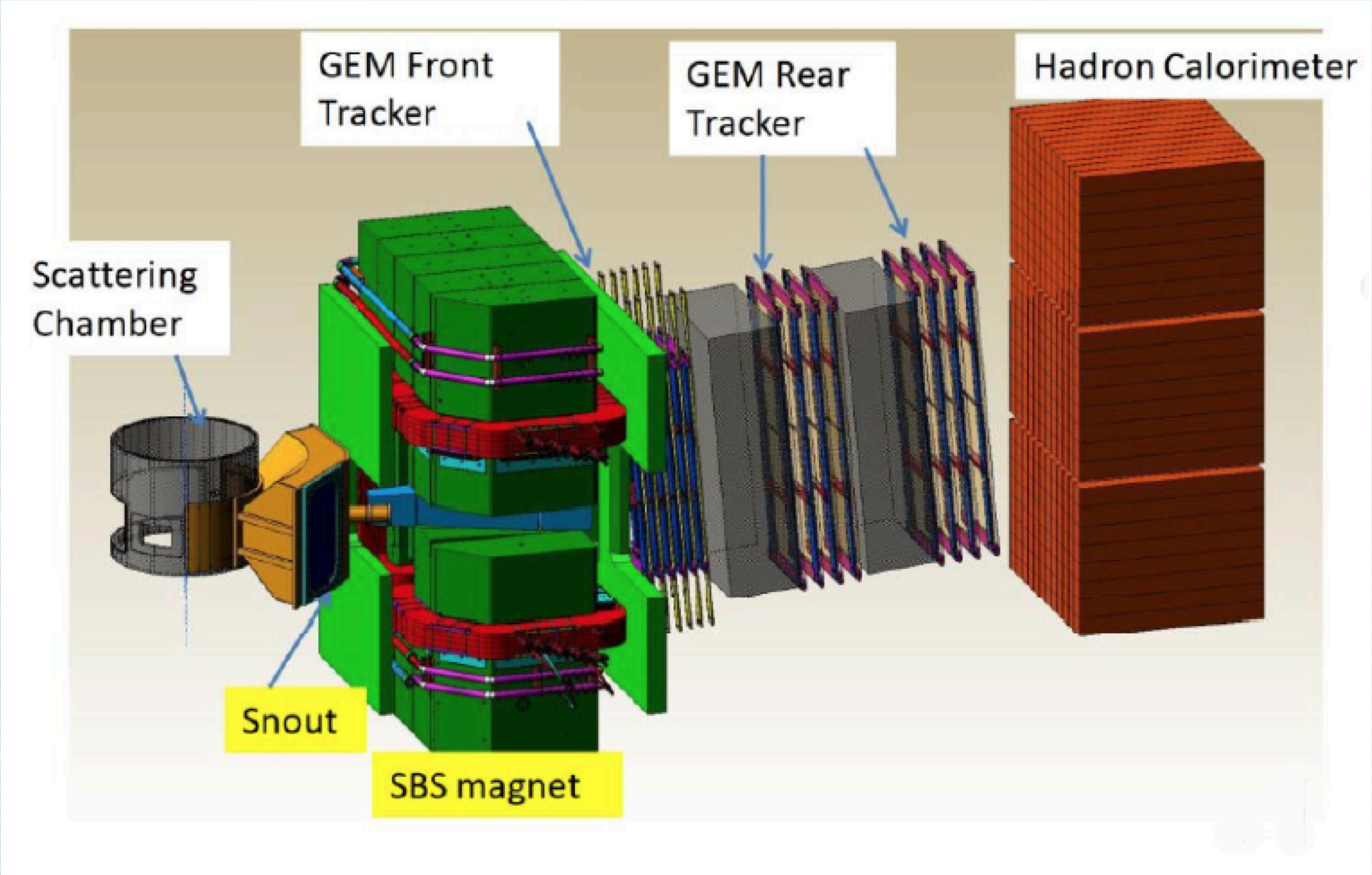
- Will have a FoM nearly 100 times higher than used at SLAC for E-142.
- <u>Spectrally-narrowed</u> high-power diode-laser arrays provide advantage over previous high-Q^2 polarized ^{3}He G_E^n experiment.
- Convection-driven target cells circulate polarized ^{3}He more quickly, allowing higher beam current (8uA -> 60uA) while maintaining high polarization of 60%.

The SBS polarized-^{3}He G_E^n experiment: projected results



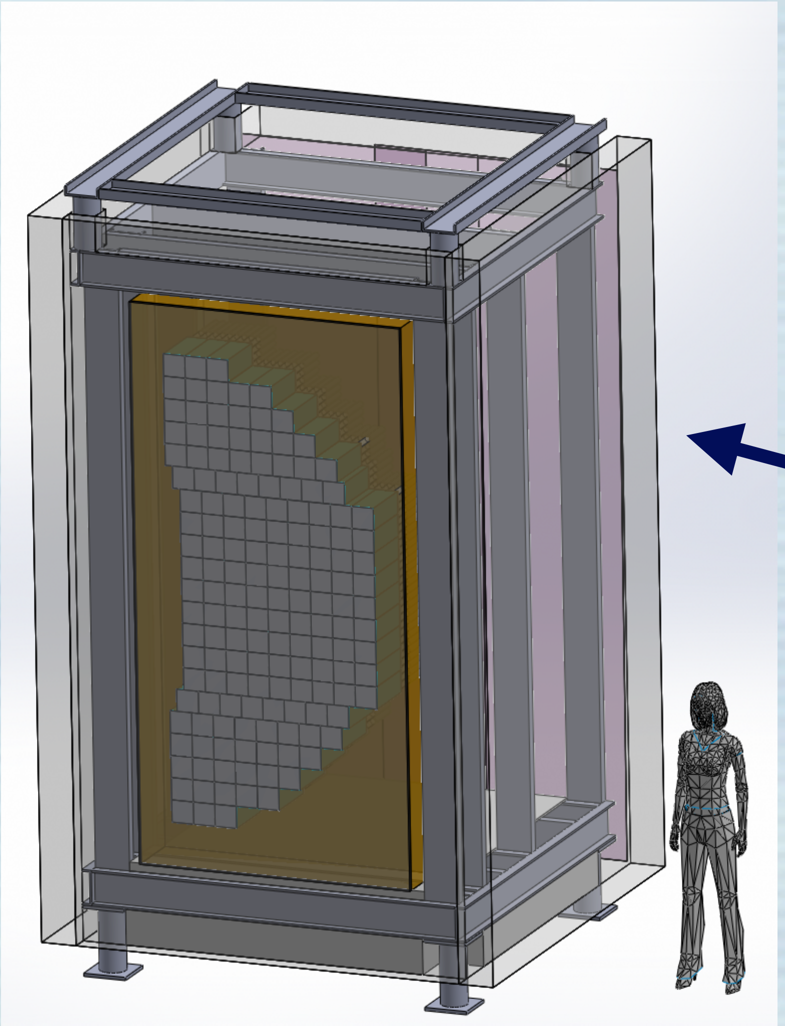
The <u>fourth</u> (and most challenging?) SBS experiment, the G_E^p experiment: E12-07-109

- Recoil polarimetry through two CH_2 analyzers using GEMs for tracking
- e^- detected in electromagnetic calorimeter with coordinate detector.
- Q^2 up to 12 GeV^2

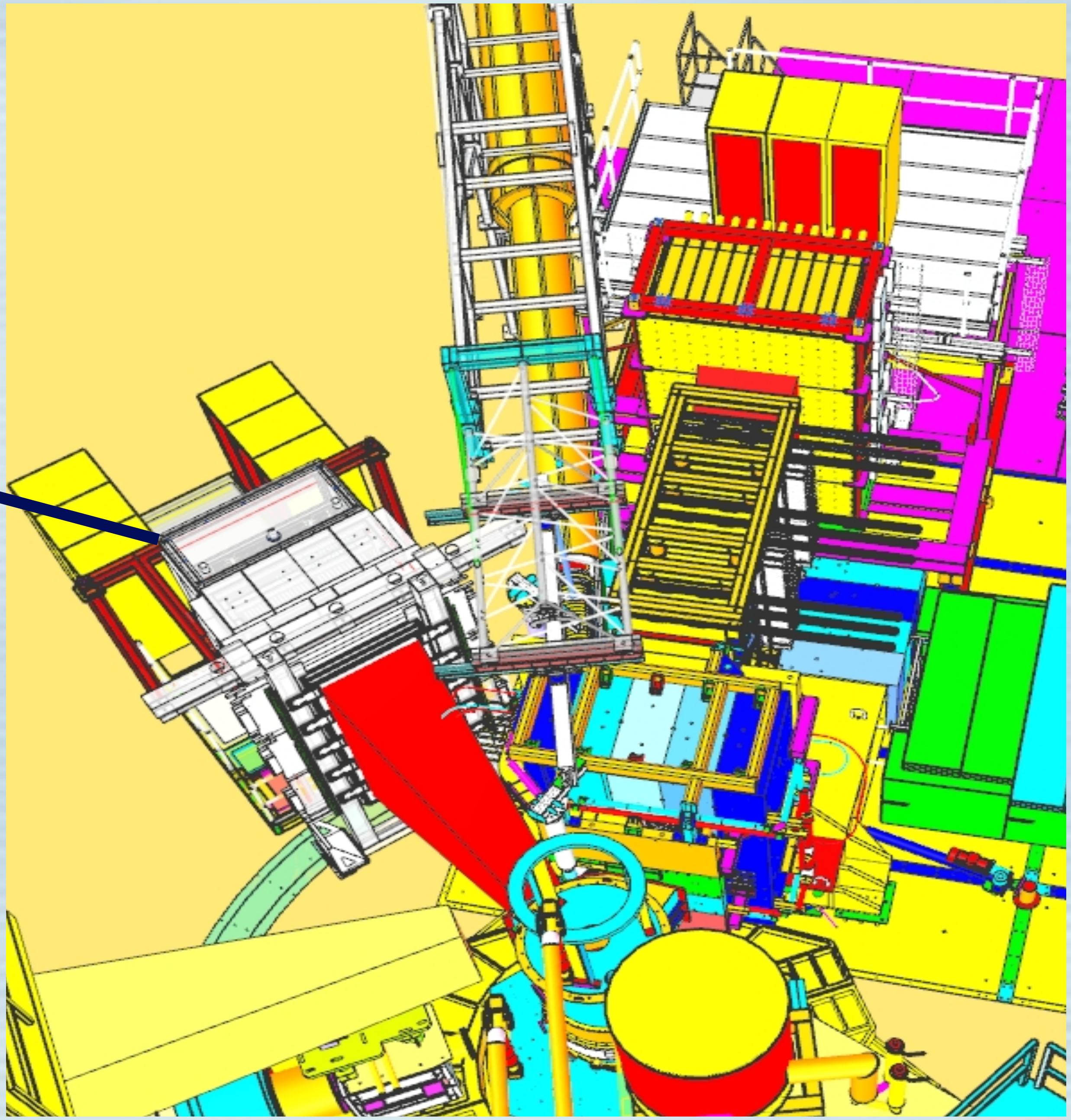


- 75 μA on 40 cm H_2 target
- θ_{hadron} down to 17 degrees
- Background rates up to 150 kHz/cm^2

The fourth (and most challenging?) SBS experiment, the G_E^p experiment: E12-07-109

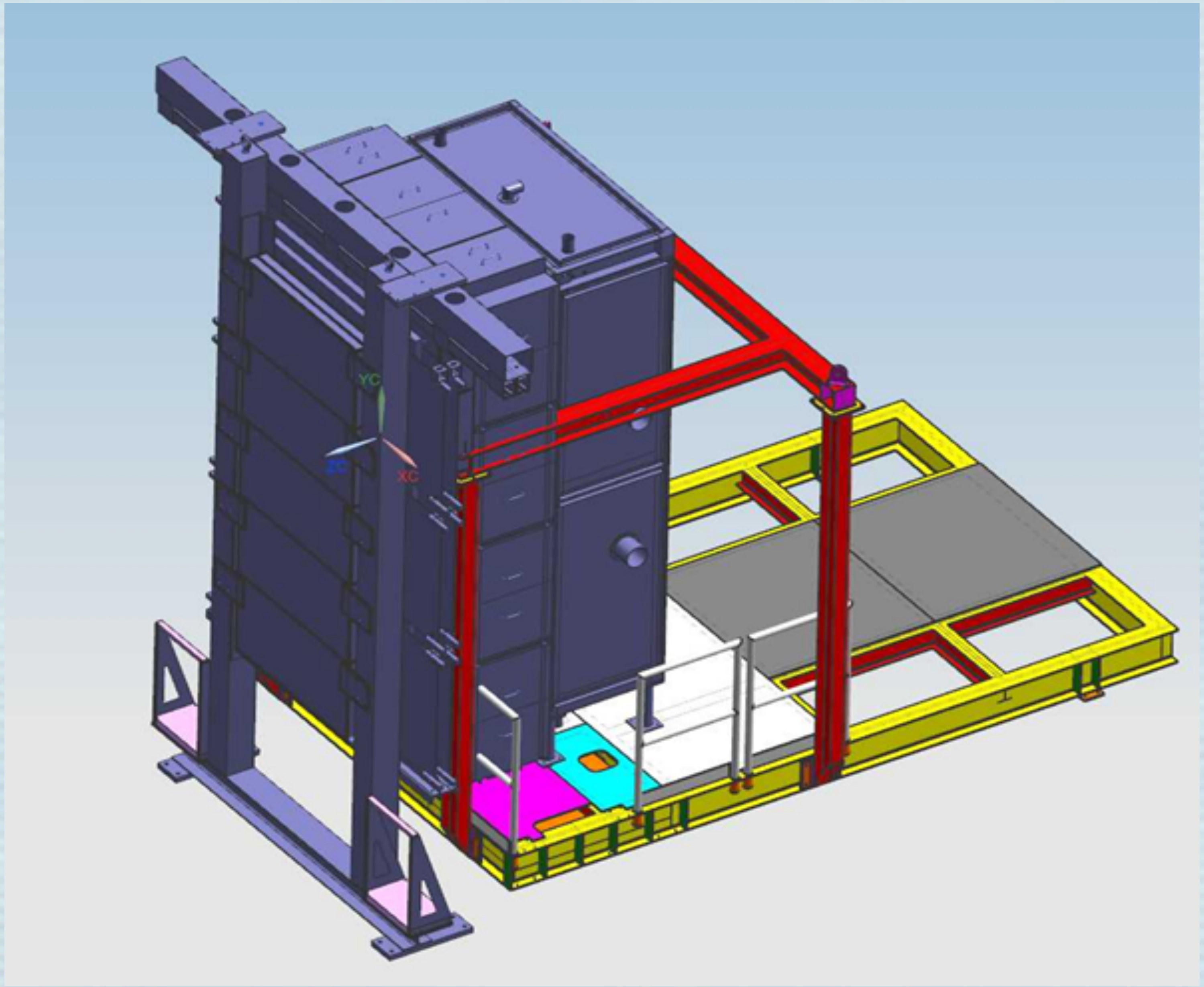


Upgraded ECal calorimeter, with human figure to give sense of scale



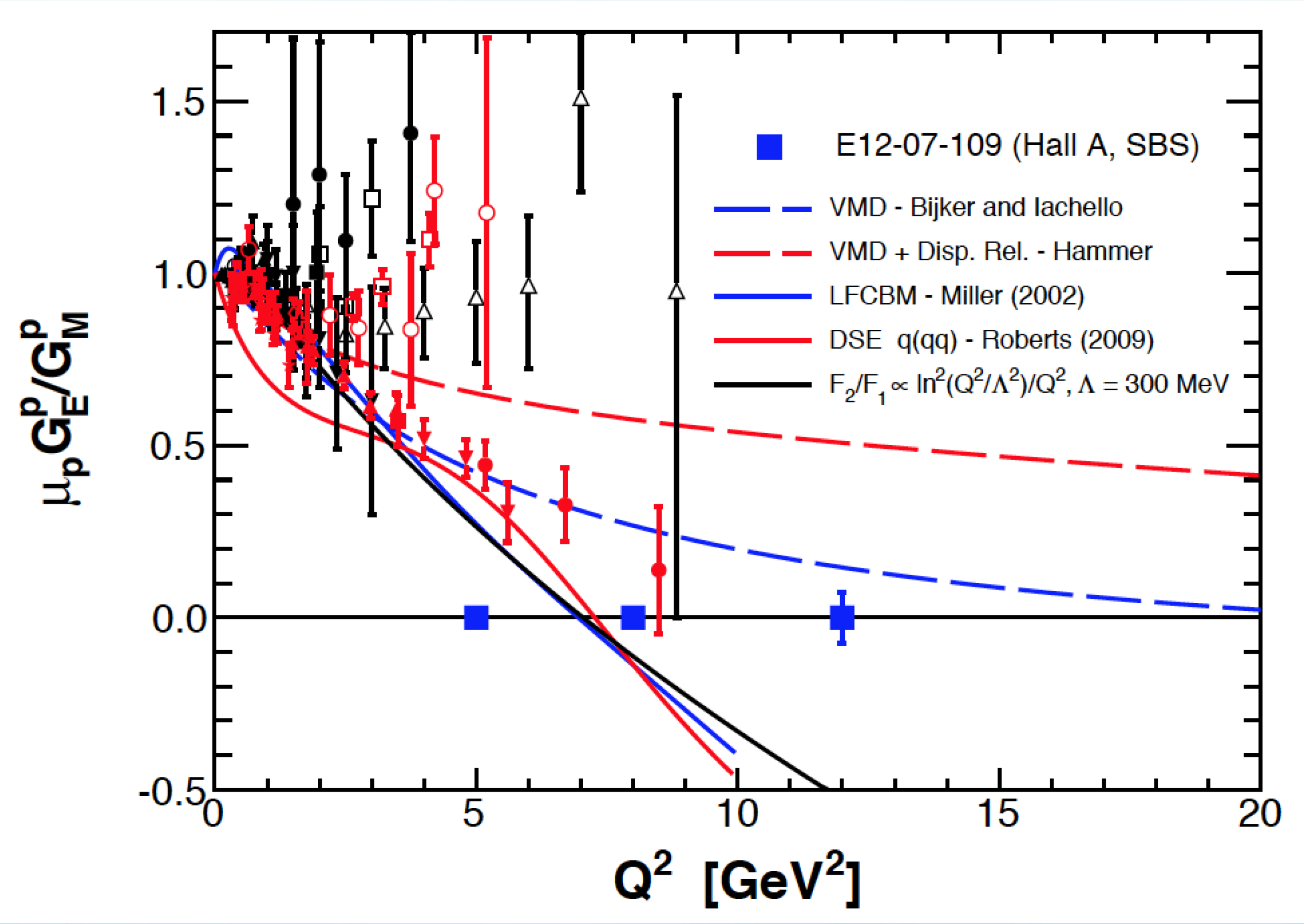
The fourth (and most challenging?) SBS experiment, the G_E^p experiment: E12-07-109

Electron calorimeter for the electron arm with NO magnetic elements.

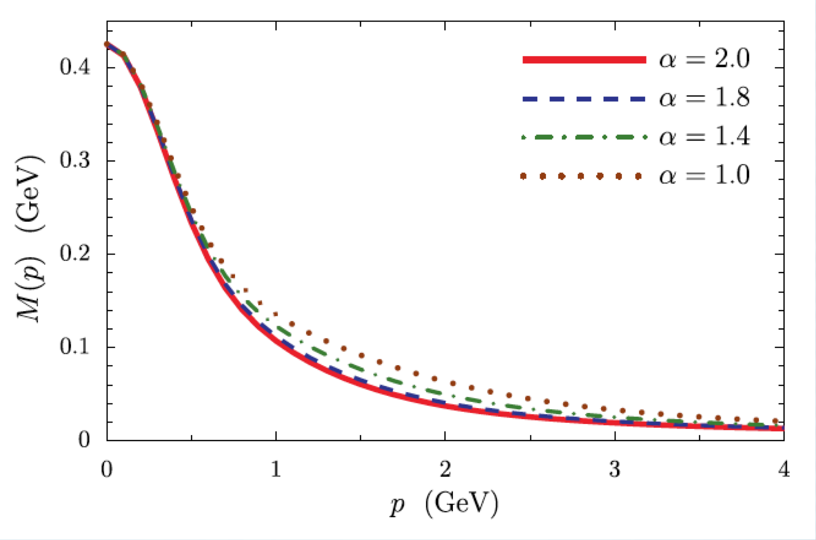


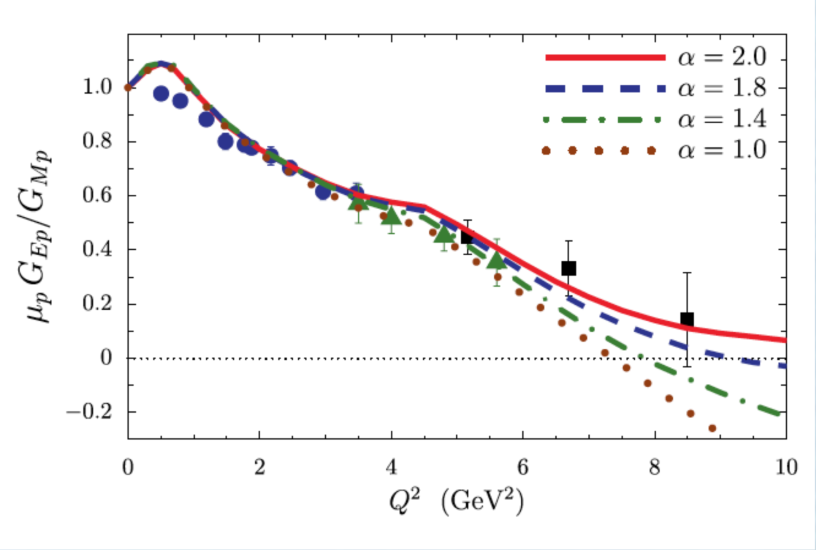
- Upgraded version of existing electron calorimeter.
- ECal will absorb 0.5 kRad/hour for Q^2 = 12 GeV^2 (no magnetic elements!)
- Thermal annealing at 200 C maintains optical transparency.
- Background rates up to 150 kHz/cm^2

The SBS measurement of G_E^p/G_M^p: E12-09-019



G_E^p/G_M^p projected data

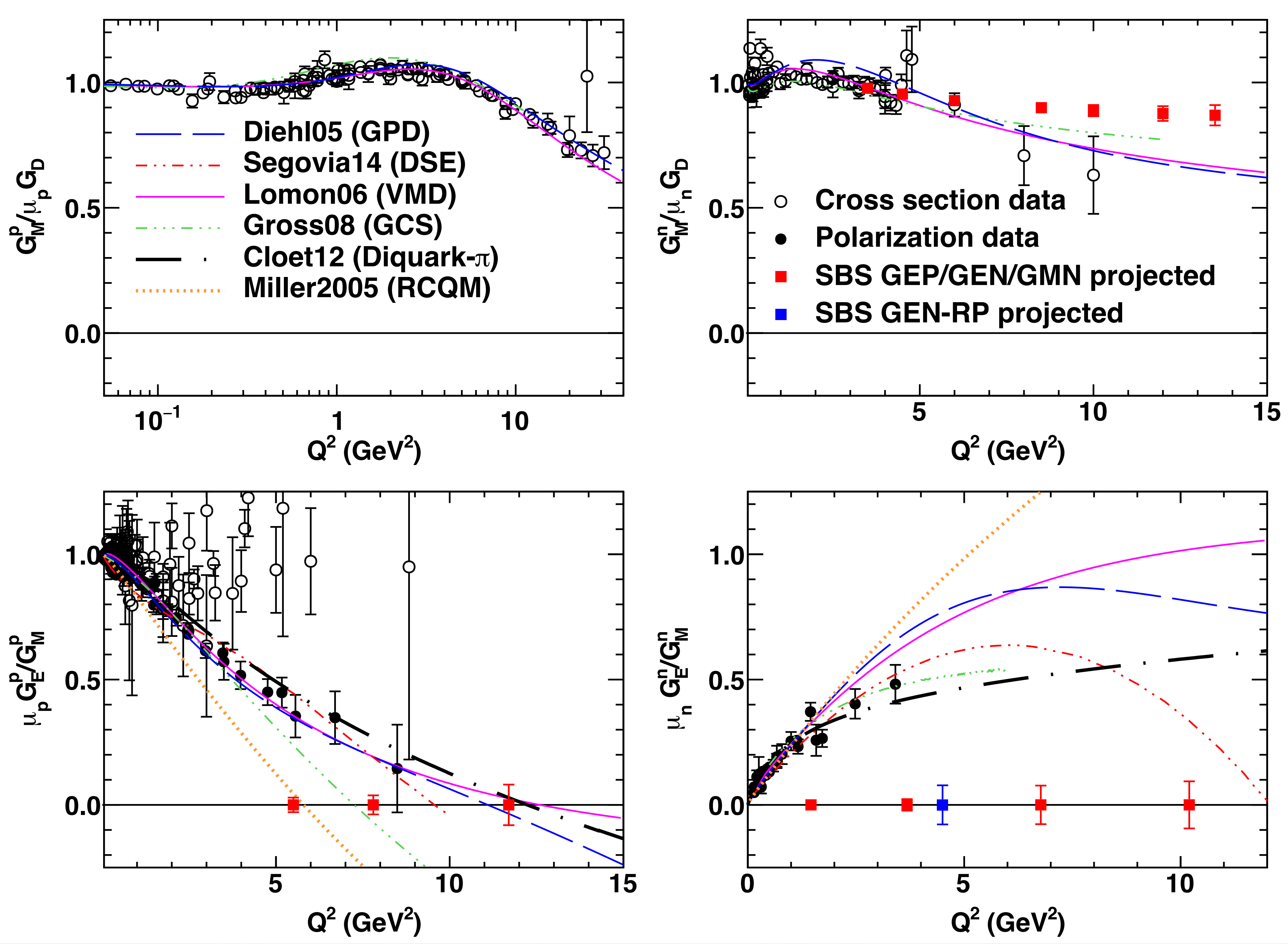




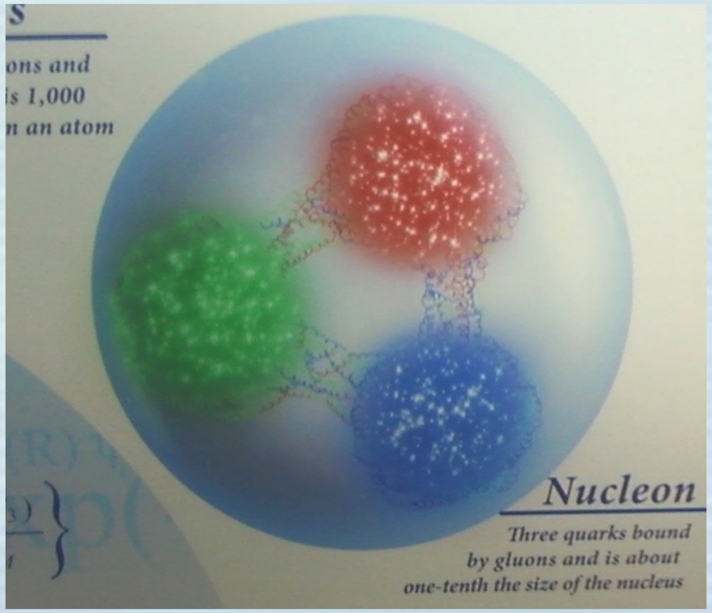
Cloet, Roberts, Thomas, PRL 111, 101803 (2013)

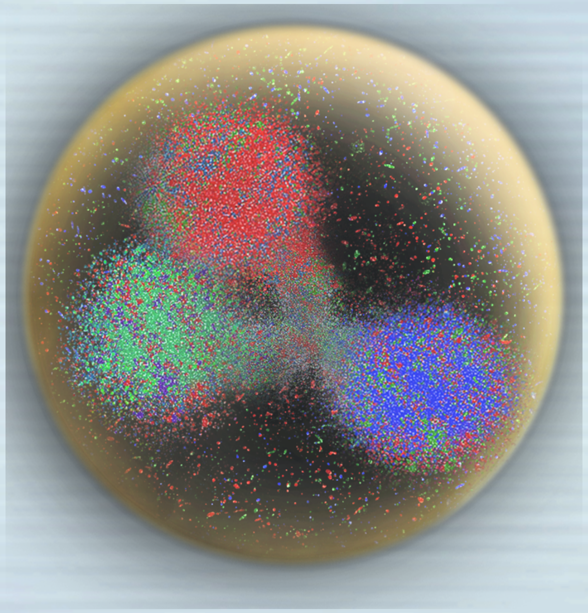
The zero crossing of G_E^p/G_M^p provides sensitivity to the mass function $M(p^2)$

Summary of SBS form-factor measurements



SBS could help shape a <u>qualitatively</u> different picture of nucleon structure





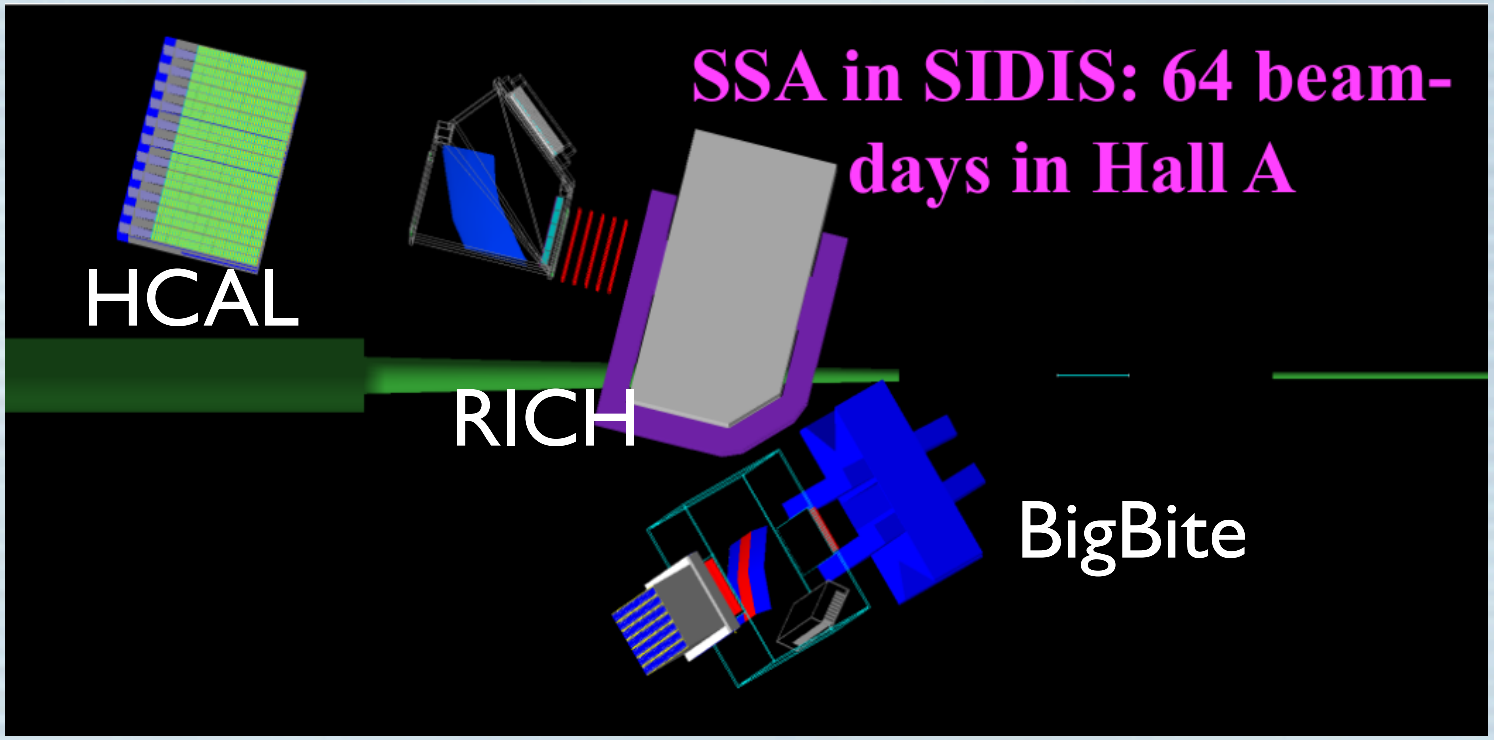
A cartoon of the nucleon from the lobby of JLab

From the DOE Pulse Newsletter: A not-very-scientifically guided depiction of a nucleon with a diquark-like structure

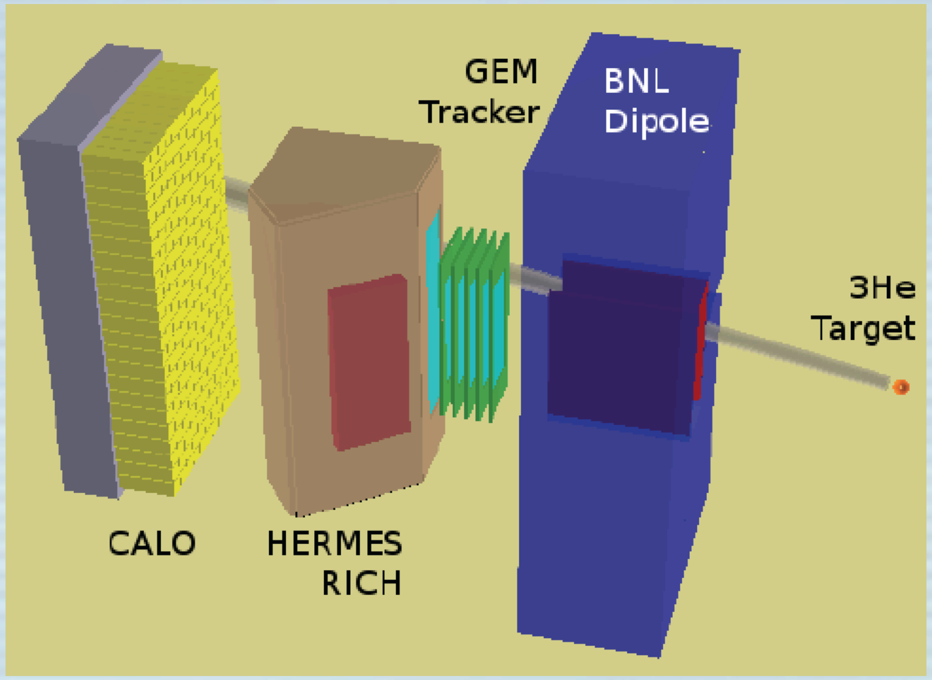
While this cartoon is WAY too simple, it illustrates how the work being discussed at this workshop might influence fundamental concepts of hadronic structure

Additional experiments beyond the elastic form factors

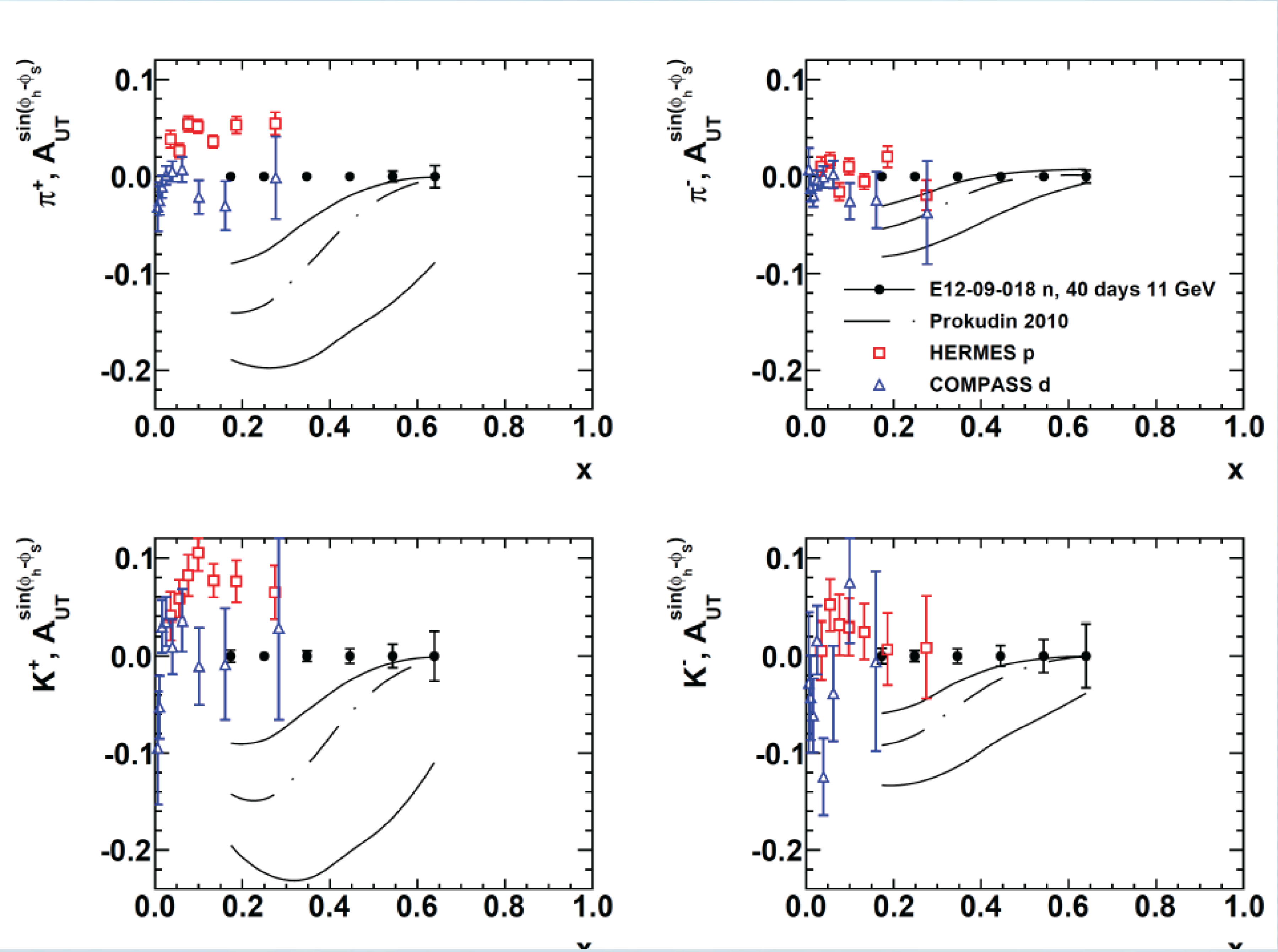
Neutron Transversity with SBS+BB
Semi-inclusive DIS: E12-09-018



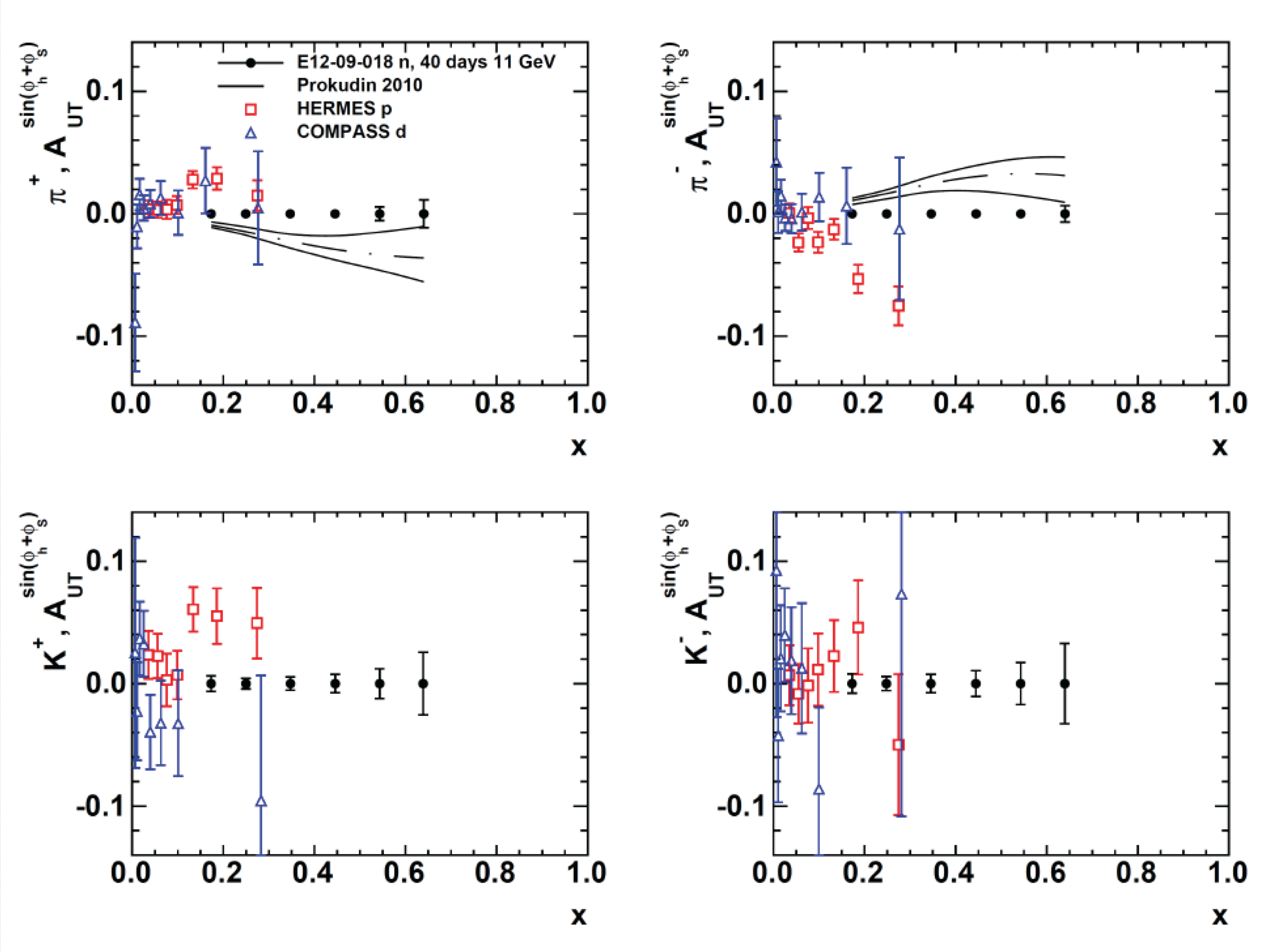
- JLab E12-09-018—approved for 64 beam-days by JLab PAC38, A- scientific rating
- Transverse target single-spin asymmetries in ^{3}**He**(e,e'h)X ($h=\pi^{\pm,0}$, $K^{\pm}$)
- ~100X higher statistical figure-of-merit for neutron than HERMES proton data
- First precision measurements in a multi-dimensional kinematic binning



SBS+BB projected results for neutron Sivers single-spin asymmetries

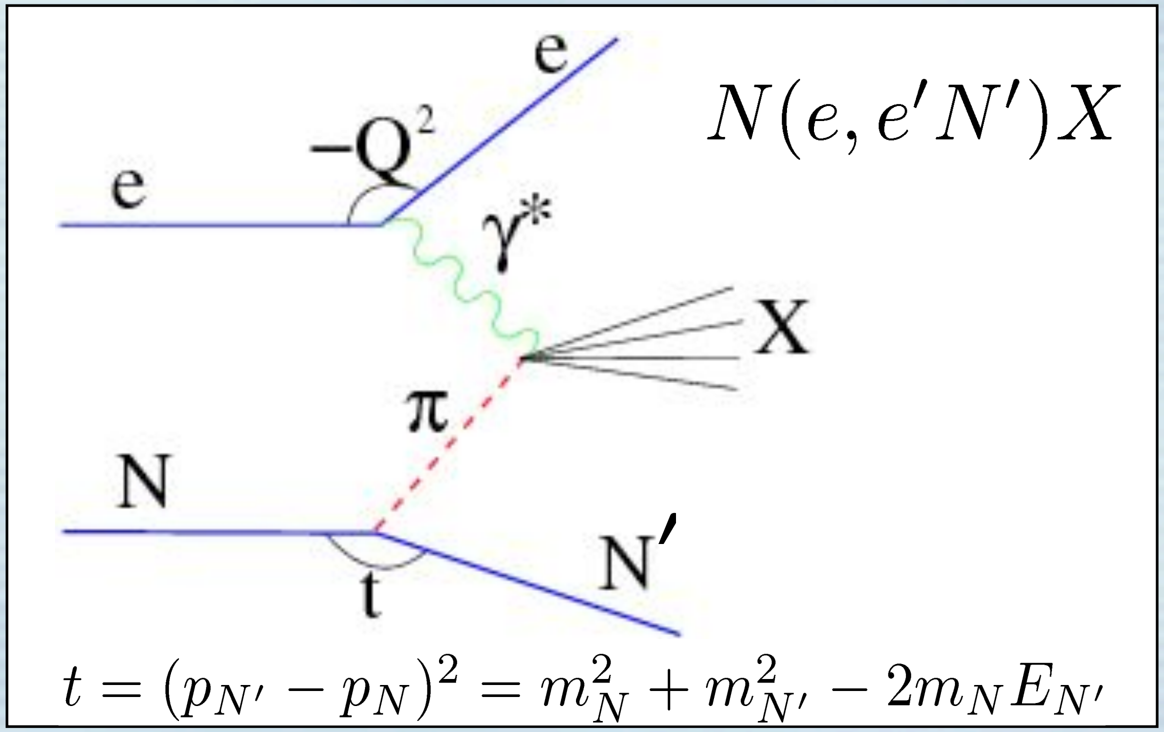


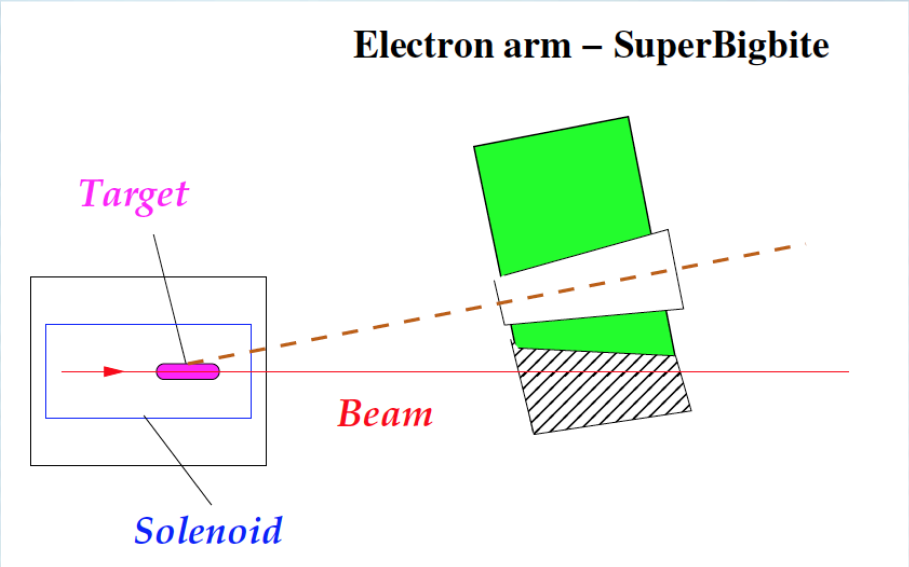
SBS+BB projected results for neutron Collins single-spin asymmetries

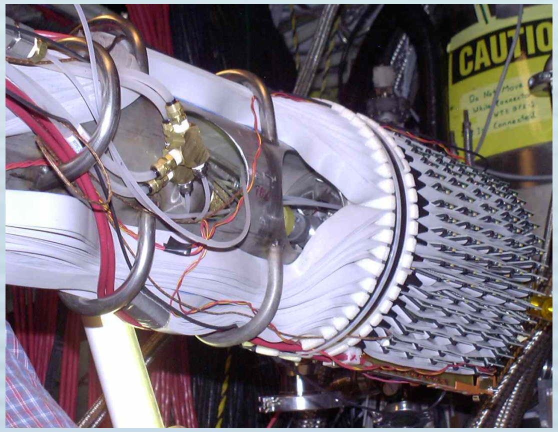


The SBS Tagged DIS experiment: PR12-15-006

Pion Exchange (Sullivan) Process -DIS from the pion cloud of the nucleon







- |t| has to be small to enhance contribution from Sullivan process -> use rTPC detection technique pioneered by JLab BONUS experiment with CLAS6
- BUT, small cross section means need luminosity – solution: use an optimized rTPC with Super BigBite, L ~ 10^{37}

Summary

- The high luminosity and large solid angles of SBS will result in excellent statistics.
- The improved knowledge of the nucleon form factors at high Q^2 has the potential to be a game changer in our understanding of nucleon structure.
- The SBS program will also include additional physics such as SSAs in SIDIS, and tagged DIS.